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THE SINGLE-SITE COLLISION AVOIDANCE SYSTEM

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16. Abstract

SS-CAS is a unique beacon collision avoidance system which works in conjunction with the current and next generation air traffic control surveillance systems (ATCRBS and DABS). In its passive mode, SS-CAS provides three dimensional position of both user and target aircraft using beacon replies from only one ground-based DABS or ATCRBS interrogator. Full collision avoidance service is provided in both the all-ATCRBS environment of today, the all-DABS environment of tomorrow, and the intervening transition period. The ground and airborne equipments required are add-ons to the ground beacon and the airborne DABS units. A two-way data link separate from, but compatible in format with, the DABS data link provides the SS-CAS-equipped aircraft with important site data. A tracker capable of reading reliable tracks through ATCRBS synchronous garble is employed. DABS replies arrive garble-free at the SS-CAS aircraft and are simple to track. An active mode and multi-site usage capability are available for performance enhancement in identified special situations.

This report fully describes the SS-CAS concept as it functions in the all-ATCRBS, all-DABS and transition environments.

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THE SS-CAS CONCEPT

Summary

SS-CAS is a unique beacon collision avoidance
system which works in conjunction with the current and
next generation air traffic control surveillance systems
(ATCRBS and DABS). In its passive mode, SS-CAS provides
three dimensional position of both user and target air-
craft using beacon replies from only one ground-based
DABS or ATCRBS interrogator. Full collision avoidance
service is provided in both the all-ATCRBS environment
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ACKNOWLEDGMENT

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

1. INTRODUCTION AND SUMMARY OF CONCEPT SS-CAS

1.1 CONCEPT SS-CAS

This report describes a unique beacon collision
avoidance system (BCAS) concept called SS-CAS (Single
Site Collision Avoidance System), which works in con-
junction with the current and next generation ground-
based air traffic control surveillance systems (ATCRBS
and DABS). SS-CAS, in its passive mode, is unique in
that it is sufficient to listen to target replies from
only a single ground-based ATC interrogator (ATCRBS
or DABS) to obtain three dimensional positions of both
target and user aircraft.

The user desiring SS-CAS service for his air-
craft adds an avionics package to his DABS equipment,
thereby acquiring protection against all transponder-
equipped (ATCRBS Mode C or DABS/ATCRBS) aircraft. This
protection is afforded in all airspace, including sectors
out of coverage by ground surveillance. In SS-CAS, each
ground-based surveillance sensor is augmented by the

addition of a modified DABS transponder (designated GB-DABS)[*] which communicates with aircraft via the omnidirectional antenna already installed at the site. The GB-DABS transponder operates at the frequencies (1030 MHz receive, 1090 MHz reply) presently assigned for ATC surveillance.

The SS-CAS-equipped aircraft: (i) receives DABS and ATCRBS replies elicited from other aircraft by ground-based sensors, (ii) receives squitter transmissions from the GB-DABS, (iii) receives squitter transmissions from airborne DABS transponders, and (iv) periodically interrogates GB-DABS and receives its reply. Using the information gained from these procedures, the SS-CAS aircraft can unambiguously determine both its own position and that of any target aircraft which poses a potential collision threat. A track file of smoothed position data is formed upon detection of a new target and is extended until the target departs from airspace of interest to the protected craft. The track file is continuously monitored by a threat detection computer, and when a threat is declared, a collision avoidance maneuver is determined. The maneuver may be unilateral or cooperative, depending upon equippage of the threat

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[*] Ground-Based DABS

aircraft. Additional support modes of operation are available for special situations and performance enhancements, e.g., active interrogation of target aircraft in regions devoid of ground-based surveillance coverage (over ocean, etc.).

1.2   KEY FEATURES

The SS-CAS concept, developed in detail in this report, is highlighted by the following key features:

- **SS-CAS PROVIDES SINGLE-SITE PASSIVE SOLUTION**
  For both the ATCRBS and DABS environments, SS-CAS provides a solution for both own and target aircraft position which requires the presence of only one ground site and only the passive reception of replies.

- **RELIABLE SS-CAS/GB-DABS DATA LINK PROVIDES SITE INFORMATION**
  The SS-CAS aircraft uses the two-way data link between itself and the GB-DABS transponder to obtain information such as site position, beacon rotation rate, PRF, etc. The link has been configured to have communication reliability equivalent to an ATCRBS link operating at the

same range. The degradation in link budget
(relative to ATCRBS) due to employment of
omnidirectional antennas at both ends is
retrieved via improved modulation and coding.
The resulting message formats conform to those
of DABS.

- **ATCRBS TRACKER READS THROUGH SYNCHRONOUS GARBLE**
Synchronous garble is unavoidable among the
ATCRBS replies received by the SS-CAS aircraft.
The elements of a tracker which can potentially
decode replies garbled by 4-6 other returns per
scan are presented herein. The tracker will
exploit azimuthal "end effects" to achieve this
goal. Garble resolution should be improved
using scan-to-scan reply correlation ("true-
zero" processing) but detailed design consider-
ation is beyond the scope of the present effort.

- **ACTIVE MODE ENHANCES LOW-DENSITY AIRSPACE
CAPABILITY**
Active interrogation is used to identify and
track targets when no ground-based surveillance
replies are available. The SS-CAS interrogator
also implements the air-to-air DABS data link
required for collaborative collision avoidance
maneuvers. Intermittent usage of active mode
in low traffic density airspace can help to
resolve an identified severe and persistent
ATCRBS synchronous garble problem.

- **SINGLE SITE DABS REPLIES GARBLE-FREE AT SS-CAS
AIRCRAFT**
The DABS interrogations used by SS-CAS for

position determination are timed so that the
replies received at SS-CAS are garble-free.
Tracking is substantially simpler than in the
ATCRBS case as a result.

- SS-CAS COMPATIBLE WITH TRANSITION FROM ATCRBS
  TO DABS
  SS-CAS offers full CAS service in an environ-
  ment consisting of ATCRBS beacons and Mode C
  transponder-equipped aircraft. During the
  period of evolutionary upgrading of the ATC
  surveillance system from ATCRBS to DABS,
  integrity of SS-CAS service will be main-
  tained. As the DABS goal is approached, the
  hardware/software requirements of the SS-CAS
  avionics become simpler.

- GROUND/AIRBORNE EQUIPMENT RETROFIT MINIMIZED
  ATCRBS or DABS sensors are modified only by the
  addition of a transponder. The airborne DABS
  unit adds a 1090 MHz receiver to monitor
  replies, a 1030 MHz interrogator, a micropro-
  cessing computer and signal processing interface
  unit to obtain SS-CAS service. Minor modifi-
  cations (on the order of a logic card replace-
  ment) in the transponder accommodate the
  GB-DABS data block formats.

- MULTI-SITE USAGE ENHANCES HIGH DENSITY AIRSPACE
  CAPABILITY
  The presence of multiple sites can be used to
  advantage in tracking both DABS and ATCRBS
  targets. In the ATCRBS case, sites from which

to track aircraft may be selected to mini-
mize the increased synchronous garble and to
improve the measurement geometry. In the
DABS case, SS-CAS can infer the DABS interro-
gation timing of adjacent sites, and targets
being interrogated by those sites can be
tracked.

1.3   FORMAT OF CONCEPT PRESENTATION

This report presents the entire SS-CAS concept
as it evolves from an ATCRBS environment to a DABS
environment. The evolution is developed in three sec-
tions. The first (Section 2) describes how SS-CAS would
work in the "all-ATCRBS" environment. This environment
is defined to represent an idealized version of today's
surveillance environment, that is, all ground-based
beacons are ATCRBS, and all participating aircraft carry
ATCRBS altitude-encoding (known as Mode C) transponders.
The SS-CAS-equipped aircraft are the sole exceptions to
the postulated environment. This topic is most impor-
tant because it defines the essential starting point for
introduction of SS-CAS into the air traffic control
arena. It is the "initial condition" which any CAS
proposal must meet in order to merit further consideration.

Section 3 describes SS-CAS functioning in an environment visualized as the goal, or endpoint, of the planned evolutionary upgrading of the present surveillance system. This environment is termed "all-DABS" and is characterized by an air traffic population in which participants carry either a DABS (ATCRBS-compatible) transponder alone, or the DABS unit _plus_ the necessary SS-CAS avionics. All surveillance beacons are DABS/ATCRBS sensors. The point of view is taken that a collision avoidance system ought to be compatible with both today's ATC systems and those presently planned, and already well under development, for the near future.

Two options are presented for the DABS environment version of SS-CAS, each reflecting a particular stance on the issue of independence of SS-CAS and ground-based surveillance. In one option, the ground cooperates by uplinking surveillance information in the data link portion of the DABS interrogations. In the second option, SS-CAS is, as in the ATCRBS case, wholly transparent to the ground. The two options have many features in common and judicious combination of these can be expected to lead to a CAS capability of superior accuracy, reliability, flexibility and independence.

The link between the snapshots of the ATC
environment discussed in Sections 2 and 3 is, of course,
the transition, or mixed, environment during which
some DABS/ATCRBS sensors have become operational, not
all ATCRBS-only beacons have been decommissioned or
converted, and the transponder population shows a mix
of ATCRBS Mode C and DABS/ATCRBS units. This situa-
tion is the subject of Section 4. Since SS-CAS has
been developed with both ATCRBS and DABS compatibility
in mind all along, the section is brief. Its dis-
cussion is in the main oriented towards those aspects
of SS-CAS which are sensitive to the relative amounts
of ATCRBS and DABS activity during the transition phase.

2. SS-CAS IN THE ALL-ATCRBS ENVIRONMENT

In the remainder of this paper, we describe conceptually how SS-CAS operates. Our approach will be to first describe the concept as it applies to an all-ATCRBS environment, the "initial condition" that any CAS must meet (this section). Next, we will present the SS-CAS concept for an all-DABS environment (Section 3). The manner in which SS-CAS evolves from an ATCRBS to an all-DABS environment is the subject of the final section (Section 4).

An all-ATCRBS environment is defined to represent an idealized version of today's surveillance environment. In this environment, there are only ATCRBS interrogators and, with the exception of SS-CAS equipped aircraft, all aircraft have ATCRBS-only Mode C transponders. A ground-based DABS transponder (GB-DABS) is colocated with each ATCRBS interrogator site [1]. Each SS-CAS aircraft has both a modified DABS transponder and a DABS/ATCRBS 1030 MHz interrogator.

Basically, in any passive CAS concept, an aircraft listens to the communication between ground

interrogators and airborne transponders to determine
the position of target aircraft. In the SS-CAS con-
cept, the use of GB-DABS transponders colocated with
the interrogator minimizes the avionics for the air-
craft desiring CAS service and significantly improves
performance, as the following discussion will show.
First, the SS-CAS aircraft can interrogate GB-DABS to
obtain a DME-type slant range measurement, eliminating
any necessity to listen to replies from more than one
ATCRBS interrogator site for a passive CAS. Secondly,
a data link is established, between the GB-DABS and the
SS-CAS/DABS, to coordinate SS-CAS with ground ATC.
Finally, the DABS transponders on the ground squitter,
at a one Hertz rate, such information as the site
identify, radar position (including altitude), main
beam azimuth angle (azimuth change pulse code), antenna
rotation rate, and pulse repetition frequency. This
information then permits the SS-CAS to compute own
azimuth and range from the radar and to initiate target
tracking with respect to that radar. The GB-DABS
squitter supplants the need for azimuthal reference
pulses. Although the squitter is transmitted omni-
directionally, its detectability has been made equiva-
lent (through choice of modulation and coding) to the

ATCRBS signal from the site. No additional sensitivity
requirements are imposed on the airborne 1030 MHz
receiver by the GB-DABS signals.

Any air-derived beacon-based CAS system must
be multi-modal to function effectively in a variety of
site dispositions and air traffic environments [2].
Each concept utilizes sophisticated on-board computer
algorithms to establish target tracks and to determine
target threats with acceptably low false alarm rates.
These various modes arise because of a close correla-
tion between air traffic density and the number of
ATCRBS sites in view of the CAS aircraft. Thus, all
CAS systems will utilize a simple interrogation mode
over oceans where the air traffic density is minimal
and where no ground-based surveillance exists. The
complexity of the mode of operation must increase with
the traffic and site density. In the single site case,
the software portion of this complexity is basically
due to the target tracker, which must read reliable
tracks through severe problems of synchronous garble.
Note that the garble problem is more severe for the CAS
aircraft than for the ground beacon because the former's
omnidirectional antenna is non-selective in listening

to replies, whereas the ground-based ATCRBS has a 4° beam to provide azimuth discrimination for its reply processor and tracker.

Although SS-CAS is the simplest of the passive CAS systems, it is still composed of many elements. Thus, we will describe the concept for an all-ATCRBS environment in three stages:

(i) an environment with no ground surveillance of target (e.g., over ocean);

(ii) a low traffic density, single site environment;

(iii) a high traffic density, multi-site environment.

2.1   SS-CAS in Regions of No Surveillance

2.1.1   Over-Ocean Mode

There is, at present, no ATC surveillance over an ocean and so each SS-CAS aircraft must operate in an active mode. An all-active mode has been described in some detail by Schuchman [3]. It differs from the other modes of SS-CAS operation in that targets

are tracked in two dimensions only (range and altitude), bearing information not being available. Here, we will simply summarize the key features of this mode of operation.

When operating actively, a SS-CAS aircraft transmits a Mode C ATCRBS interrogation (altitude request) once per second as described in Figure 2-1. The received reply carries target altitude information. The interrogation round trip time, t, is converted to provide one-way range information ($r - ct/2$, where c is the speed of light).

Since a good many transoceanic aircraft can be expected to be CAS-equipped (for future higher density oceanic routing), means of communication between two aircraft must be available in order to avoid "tie breaker" collisions due to identical conflict resolution commands having been issued by the SS-CAS of each of two conflicting aircraft. This means of communication is provided by the DABS data link. Since each SS-CAS aircraft is by definition DABS-equipped, an aircraft can transmit his intended maneuver to the target DABS-equipped aircraft, which will enable
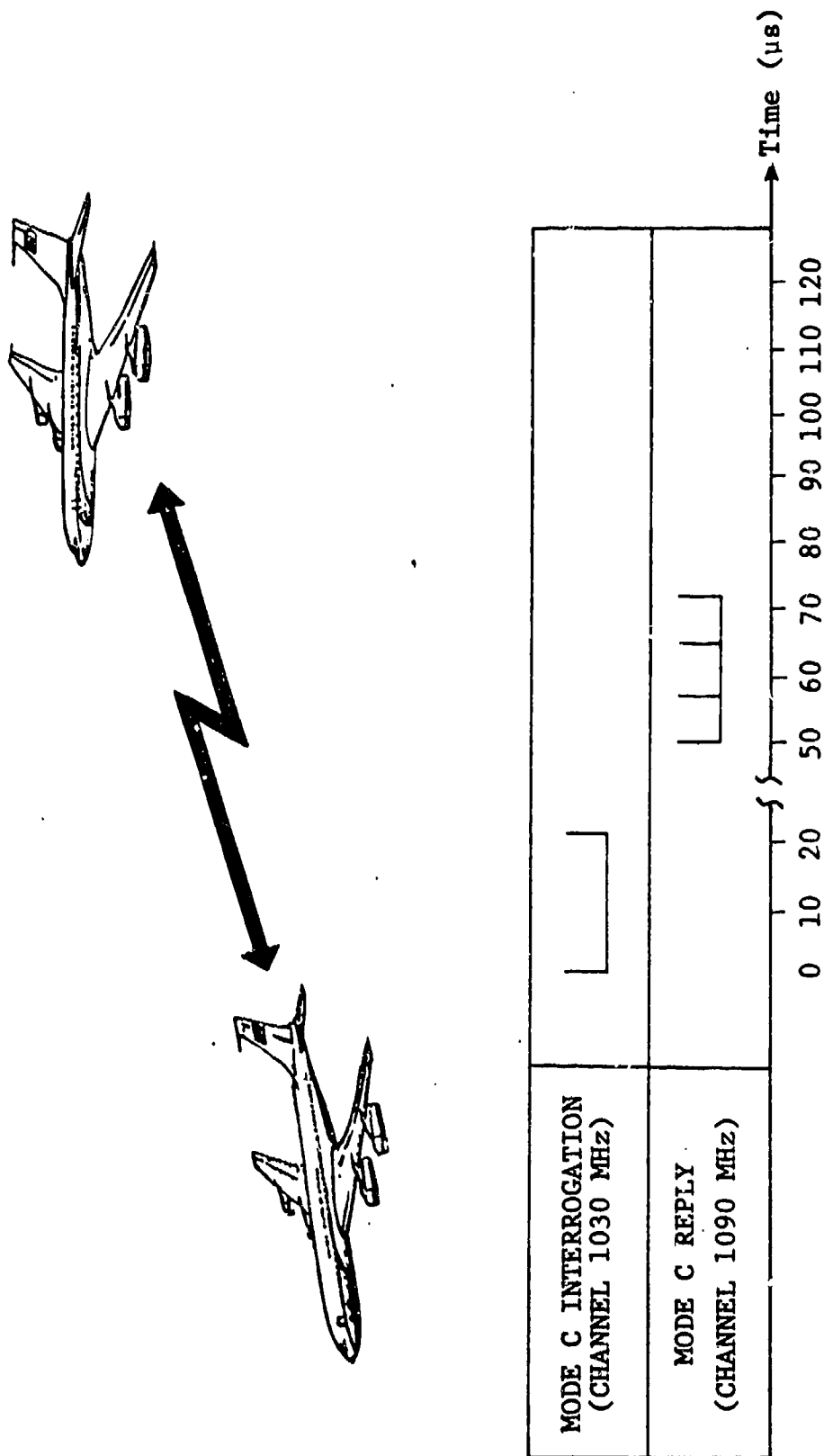
Figure 2-1. Active Mode Interrogation and Reply Message Sequence

coordinated and enhanced conflict resolution maneuvers by both aircraft (e.g., aircraft A climbs, while aircraft B dives).

In order to utilize this air-to-air data link, the target DABS ID must be known. This information is obtained from the squitter mode of the DABS transponder aboard the target [4]. SS-CAS can then interrogate the target. The responses confirm ID and provide range and altitude. Interrogations can be carried out at a low rate until a target is assessed as a threat at which time the rate is stepped up. In the event that the target is ATCRBS-only, the SS-CAS aircraft can maneuver to resolve the conflict with assurance that the complementary maneuver is not being carried out by the non-CAS aircraft.

Since major synchronous garble problems are highly improbable over the sparsely aircraft-populated ocean, the tracker design for this mode is relatively simple. A reasonable tracker design for this mode is described in Reference 3.

2.1.2   Pop-up Targets

A second situation in which potential colli-
sion threats have no ground-based surveillance is
referred to as the "pop-up" target. The pop-up is an
aircraft which is outside the coverage of the ground
site. Typically, such an aircraft is low and near the
coverage fringe of the site. If the target gains
altitude and comes into coverage, it can usually be
tracked by the single site methods given in the follow-
ing section (2.2). The difficult exception is the
case in which the SS-CAS aircraft is flying so low that
there is insufficient time to allow for proper threat
detection and execution of an avoidance maneuver.
Although the pop-up is a special case of the single-
site situation, it is treated here because the solution
involves active tracking, as in the oceanic environ-
ment.

A target out of surveillance by the ATCRBS
beacon is not passively detectable inasmuch as it
emits no replies. SS-CAS can in principal avoid the
pop-up phenomenon by issuing a Mode C interrogation
once every 4 seconds and looking for new target re-

ports, especially those indicating low flight levels. When such a target is detected and is sufficiently near or has a closing range rate, the interrogation rate can be stepped up for more accurate tracking.

The problem which could occur, however, in a moderately dense environment is that the replies from other nearby aircraft might garble the pop-up return and disguise it. To circumvent a possible garble problem, the interrogation by SS-CAS can be timed so that it arrives at aircraft near SS-CAS while they are in suppression from a recent interrogation by the beacon. Those aircraft within ground coverage will not reply; those outside coverage (i.e., pop-ups) will not be suppressed and will issue a reply. Since the number of out-of-coverage craft should be small compared to the in-coverage population, active self-garble among the pop-ups should be negligible. Of course, aircraft within coverage that have not been interrogated recently enough will also respond; the following geometric argument shows that there is nevertheless a clear volume around the SS-CAS aircraft which is sufficient to permit adequate threat detection of pop-ups.

A detailed analysis of the geometry shows that
aircra   within a sphere of radius $\frac{1}{2}R_s$ (where R_s is
the "suppression radius," i.e., the distance a signal
can travel during the suppression time T_s) will be in
suppression when the interrogation from SS-CAS arrives.[*]
The limits on T_s are defined as 35 ± 10 μs since all
transponders suppress for at least 25 μs there is a
clear radius of at least 2.37 mi within which no main-
beam targets will reply to garble out-of-coverage
targets. Within the spherical shell of inner radius
2.37 mi and outer radius 4.76 mi (45 μs), some mainbeam
aircraft may reply, depending on the suppression time
of their transponders. Unless the traffic density is
extremely heavy, their numbers and reply probabilities
should keep the mainbeam active garble to a tolerable
level.

If SS-CAS is at the coverage fringe (100 mi),
the ATCRBS beam (4°) will be 7 mi across, showing that
all aircraft within the $\frac{1}{2}R_s$ sphere are also in the main

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[*] The actual region is a hyperboloid of revolution
which contains the sphere of radius $\frac{1}{2}R_s$.

beam (when SS-CAS is at the beam center). When SS-CAS
is closer to the beacon, the main beam is narrower,
but then the ATCRBS coverage will be lower and cor-
respondingly, there should be less of a pop-up problem.

The timed interrogation technique discussed
above offers some protection against pop-up targets,
but does not guarantee detection of all of them at the
range required to establish a full confidence level
track before declaring a threat.

2.2   SS-CAS in a Low Traffic Density, Single
          ATCRBS Site Environment

It is recognized that there will be some low
density airspace over CONUS which has no ATCRBS coverage.
In such airspace, the SS-CAS continues to operate in
the all-active mode described above. This active
operation should pose no significant garble threat to
adjacent airspace due to the paucity of both traffic
and interrogators. The focus of attention in this
section, then, is SS-CAS operation within the airspace
covered by a single ATCRBS site (i.e., within a 100 mile
radius of the ground site), where a passive solution
exists.

2-11

The remaining subsections of Section 2.2 will cover:

- The SS-CAS geometry and the set of measurements which SS-CAS makes to allow it to determine target position;
- The SS-CAS/GB-DABS data link;
- The single site SS-CAS operation; and
- The principles underlying the SS-CAS tracker.

2.2.1   Geometry and Target Position Measurement Algorithm

We will start by describing the SS-CAS geometry with the help of Figure 2-2. The SS-CAS aircraft (S), the ATCRBS beacon (B), and the intruder or target aircraft (T) are shown. It is desired to determine the range to T (R_3), the bearing angle to the target (β) and the relative altitude of the target (Δh). We shall find that the information available in the observable signals is sufficient for the SS-CAS aircraft to determine its own position relative to the site; hence, the target's coordinates are known both

relative to SS-CAS <u>and</u> to the site.

Since the full position determination algorithm
is somewhat complex conceptually, albeit simple to
implement, we will explain it in two steps. Initially,
we will make the simplifying assumptions that both the
SS-CAS aircraft and the target aircraft are stationary
in space and the ATCRBS beacon main beam has essentially
no azimuthal width (the latter assumption eliminates
multiple hits per scan). In the second step, we will
remove these idealized assumptions by introducing cor-
rection factors which compensate for aircraft relative
motion, time lapse between measurements, and antenna
beamwidth.

Referring to Figure 2-2, it is easy to show
that a sufficient set of data for locating the two
aircraft is R_1, Ψ_S, Ψ_T, R_2 and the three altitudes
h_B, h_T, and h_S. Under the above simplifications, the
SS-CAS aircraft indirectly obtains these parameters
in the following ways:

2-13
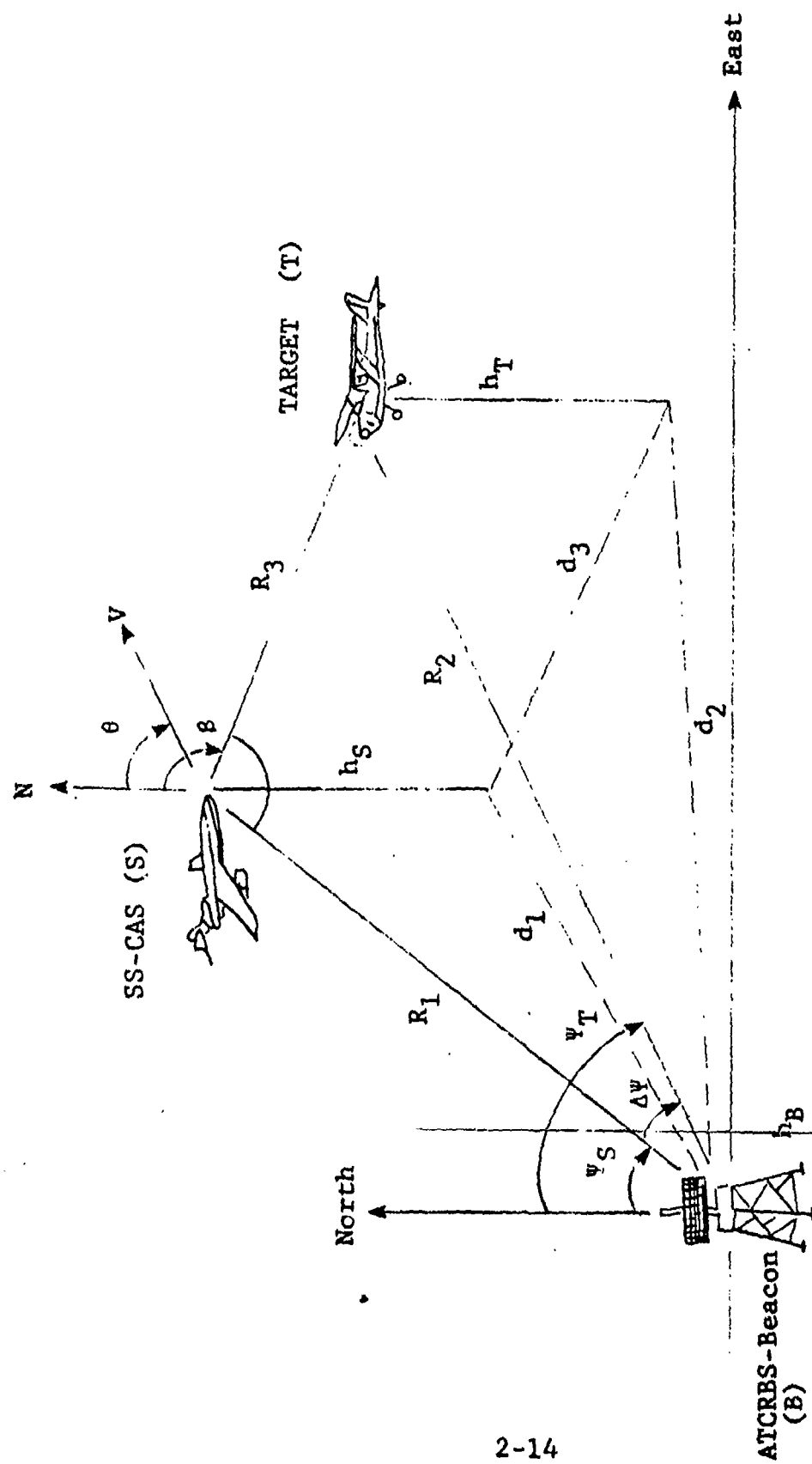
Figure 2-2: Single Site Geometry: All-ATCRBS Environment

2-14

a) R_1 (Range-SS-CAS to Beacon)

The round trip time δt_1 from the SS-CAS aircraft to the ATCRBS beacon is measured by interrogating the GB-DABS once every four seconds. This measurement directly converts to distance R_1 ($R_1 = c\delta t_1/2$, where c equals the speed of light).

b) Ψ_S (SS-CAS Azimuth)

The following are measured:

- The time of arrival of the most recently received squitter (t_{oS}), which was transmitted when the main beam pointed North, South, East, or West;

- The time of arrival of the ATCRBS main beam interrogation (t_1);

- The beacon antenna pointing angle at the time of squitter (Ψ_B) (decoded directly from the squitter - See Section 2.2.2);

- The antenna rotation rate (W_R) (decoded directly from the squitter).

2-15

Then,

$$\Psi = \Psi_B + W_R(t_1 - t_{oS})$$

c) Ψ_T (Target Azimuth)

Two methods are available. The first
measures Ψ_T directly, the second deter-
mines $\Delta\Psi$. For either, the receiver
measures:

- The time of arrival of the target
  reply to the main beam interroga-
  tion (t_{2+3}).

The direct measurement uses the most
recent squitter arrival time t_{oT}, (as
defined in b)) prior to the reply arrival
time t_{2+3} as follows:

$$\Psi_T = \Psi_B + W_R(t_{2+3} - t_{oT})^*$$

The differential measurement is:

$$\Delta\Psi = W_R (t_{2+3} - t_1)^*$$

$$\Psi_T = \Psi_K + \Delta\Psi$$

---

* This formula neglects the path delay along the portion
equal to BTS minus BS (See Figure 2-2), but this is
generally insignificant (on the order of 0.01°) due to
the slow rotation rate of the antenna.

2-16

The differential method is preferred
when SS-CAS and target reply to the
same interrogation. Otherwise, prefer-
ence is determined according to which
is more recent, t_o or t_1.

d) R_3 (Range - SS-CAS to Target)*
The measured arrival times t_1 and t_{2+3}
are required. In addition,

   - The interrogator PRF is demod-
     ulated from the GB-DABS squitter.

The parameters N_{12} and ε_{12} are defined
as follows:

$$N_{12} + \varepsilon_{12} = (t_{2+3} - t_1) * PRF$$

where N_{12} = nearest integer value ($\pm$), and

   $0 < \varepsilon_{12} << 0.5$.

Then the target is replying to an inter-
rogation which occurred N_{12} sweeps

---

* The equations given below apply as given only to a
uniform PRP interrogator. Obvious modifications are
made if the interrogator uses the jittered or staggered
interrogation sequence.

<u>after</u> the SS-CAS interrogation ($|N_{12}|$ interrogations <u>before</u> if N_{12} is negative). The fractional part ε_{12} is proportional to the differential time of arrival ΔTOA which is the time which would elapse between SS-CAS reply and SS-CAS receipt of target reply if both were interrogated on the same sweep:

$$\Delta TOA = \varepsilon_{12}/PRF$$

Then,

$$\Delta R = R_2 + R_3 - R_1 = c*\Delta TOA$$

Note that this method of obtaining ΔTOA does not require detection of the omnidirectional SLS pulse (P_2 pulse correlation). The reason is that using only the available data and on-board clock, interrogation times can be precisely predicted and need not be measured, even for beacons which jitter or stagger their interrogations. No additional sensitivity requirements are imposed on the airborne 1030 MHz receiver by the ATCRBS position measurement algorithm.

To get R_3, compute

$$\Delta\Psi = \Psi_T - \Psi_S$$

$$R_2 = \frac{\Delta R(\Delta R + 2R_1)}{2[\Delta R + R_1(1 - \cos\Delta\Psi)]}$$

$$R_3 = \Delta R + R_1 - R_2$$

e) h_B (Beacon Altitude)

The altitude of the ATCRBS beacon, h_B, is obtained from the GB-DABS squitter.

f) h_T (Target Altitude)

The altitude of the target, h_T, is obtained from the target's Mode C reply.

g) h_S (SS-CAS Altitude)

The altitude of the SS-CAS aircraft, h_S, is obtained from the SS-CAS encoding altimeter. Then

$$\Delta h = h_T - h_S$$

h) (Target Relative Bearing)

First, compute the ground projection of R_1 and R_2 (d_1 and d_2, respectively):

$$d_1 = [R_1{}^2 - (h_S - h_B)^2]^{\frac{1}{2}}$$

$$d_2 = [R_2{}^2 - (h_T - h_B)^2]^{\frac{1}{2}}$$

In the North/East coordinate system shown in Figure 2-2, the ground-plane coordinates of SS-CAS and target are

2-19

$$N_S = d_1 \cos \Psi_S$$
$$E_S = d_1 \sin \Psi_S$$
$$N_T = d_2 \cos \Psi_T$$
$$E_T = d_2 \sin \Psi_T$$

Two algebraic signs are computed to denote the sign of the target aircraft's North and East coordinates relative to SS-CAS:

$$\sigma_N = \text{sgn} \ (N_T - N_S)$$
$$\sigma_E = \text{sgn} \ (E_T - E_S)$$

Then the target bearing

$$\beta = \tan^{-1} \left[\frac{E_T - E_S}{N_T - N_S} \right]$$

can be assigned the proper value within $0^\circ \le \beta < 360^\circ$ by determining the quadrant in which it lies from σ_N and σ_E.

Thus, for the simplified static assumptions given above, the position determination algorithm is complete.

The real world differs from the above model in that the two aircraft are moving and the antenna

beam has an effective width of 4° (2.3° at the -3 dB points). Because of the relative motion of the aircraft, measurements which are made at different instants of time have to be referred to a common time base. Therefore, the SS-CAS and target positions, which are measured every 4 seconds, must be tracked so that accurate estimates of their values can be found at the required reference times. In addition, a mainlobe beamwidth of 4° is too wide for obtaining SS-CAS bearing information without some form of beam-splitting. Fortunately, an aircraft will be interrogated with as many as 16 sweeps/scan by the main beam, and estimates of azimuth which are accurate to within $1/2^\circ$ can be obtained from the resulting hits using a sliding window detector type algorithm. The detector essentially attempts to determine the beam pointing angle (center-mark of a set of target hits) (See Reference 5 for a description of the centermark used in the ATCRBS reply processor). A similar averaging is applied to the ΔTOA measurements in finding differential range. If a jittered or staggered interrogation sequence is used by the site (this will be known by the squitter), the SS-CAS aircraft must monitor sufficiently many sweeps to find the phase of sequence before it can initiate tracking.

The time instant to which all the measure-
ments are referenced is the instant estimated to be
the time of passage of the main beam center at the
SS-CAS aircraft. When the interrogations are staggered
or jittered, it may be preferable for computational
purposes to project the times onto a more nearly uni-
form grid. The assistance of the tracker is required
to provide smoothed estimates of the range and azimuth
coordinates and their derivatives. The equations
given in Table A-1 of the Appendix show how the result-
ing correction factors are incorporated.

In summary, then, the dynamics of the air-
craft movement and the use of a multiple hit/scan
interrogation rate requires the SS-CAS computer to take
measurements made sequentially in time and reference
them to a given instant of time. The SS-CAS computer
can do this with great accuracy since it tracks its
range to the beacon, centermarks for accurate azimuth
determination and accounts for target aircraft dynamics
by tracking both its own position and that of the target
with a second order α-β tracker. The method of position
determination outlined in Table A-1 is also flow-
charted in Figure 2-3.
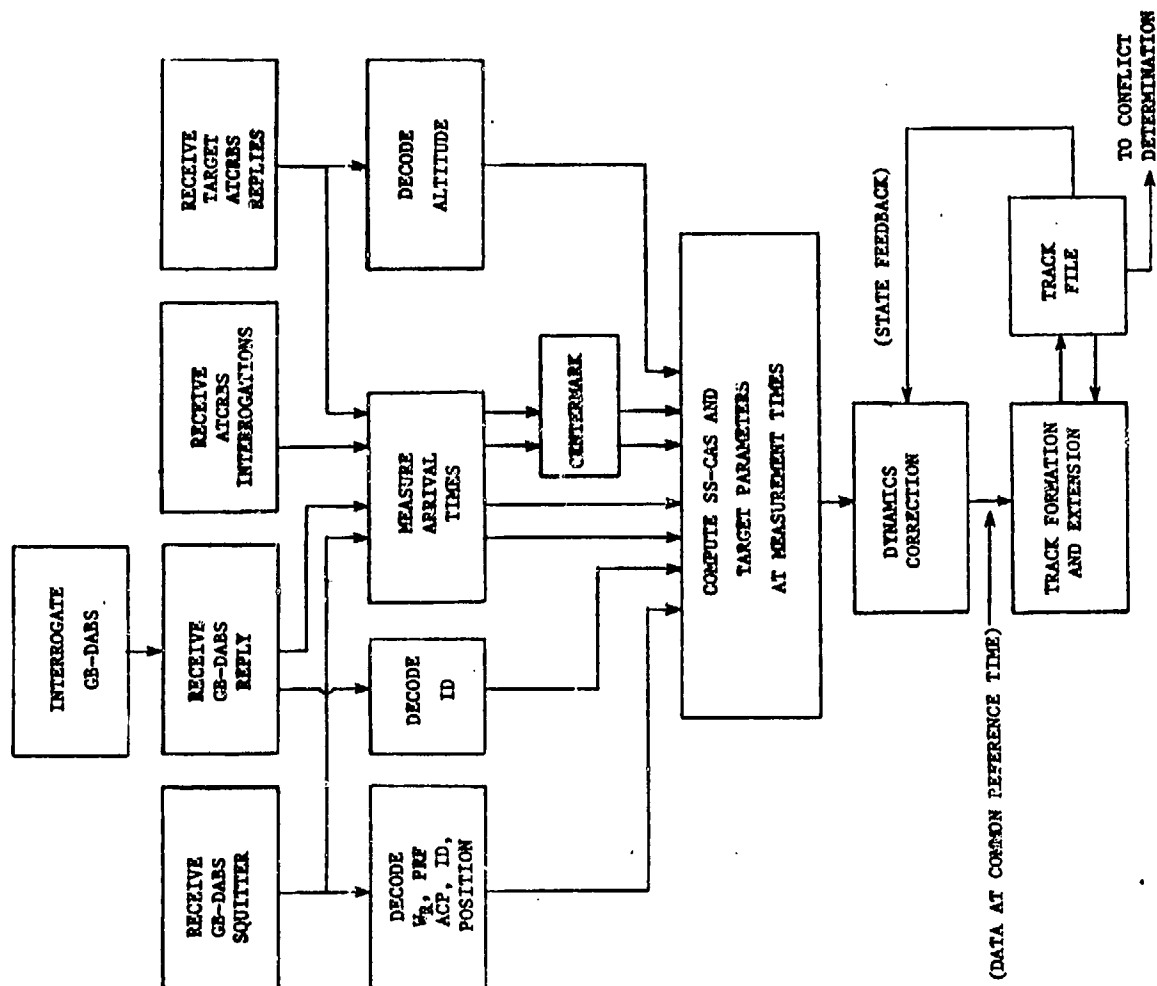
Figure 2-3: Flow Chart of Position Determination Algorithm, ATCRBS Environment

2.2.2   SS-CAS/GB-DABS Data Link

In this section we give the design considera-
tions which permit definition of the SS-CAS/GB-DABS
data link. These considerations consist, in the main,
of link budgets and signal formats. Three links are
of concern: (i) SS-CAS interrogation of GB-DABS,
(ii) GB-DABS reply, and (iii) GB-DABS squitter.

The ground based transponder is basically
a modified DABS transponder transmitting via an omni-
directional antenna. Thus, the system employs com-
munication links utilizing omnidirectional antennas
at both ends. The advantage of such links is that
installation is both simple and relatively inexpensive.
The disadvantage is in the loss of roughly 20 dB antenna
gain relative to the ATCRBS surveillance link. Table
2-1 describes how this loss is recovered by changes in
transmitter power and/or modulation format.

The essential principle underlying the design
of this data link is that the link will function
acceptably if its communication reliability can be made
equal to that of the ATCRBS link. This claim can be

Table 2-1

SS-CAS/GB-DABS Data Link Compared to
ATCRBS Transponder/ATCRBS Interrogator Data Link
(100 to 200 mile range)

GB-DABS Transponder versus ATCRBS Transponder

TRANSMIT   (Up-Link)

Transmitter Antenna Gain [360° vs 4° beamwidth]	-19.5 dB
Pulse Chip Width [1 µs vs 0.45 µs]	+ 3.5 dB
Modulation [PPM vs PAM]	0.0 dB
Power [1.25 kW vs 125 W]	+10 dB
Number of Chips per Bit [4 vs 1]	+ 6 dB
Net Gain (Loss)	0.0 dB

RECEIVE   (Down-Link)

Receiver Antenna Gain	-19.5 dB
Pulse Chip Width [0.25 µs vs 0.8 µs]	- 5.0 dB
Modulation [DPSK vs PAM]	+ 6.0 dB
Power [1.25 kW vs 125 W]	+10.0 dB
Number of Chips per Bit [7 vs 1]	+ 8.5 dB
Net Gain (Loss)	0.0 dB

made on the grounds that the current ATCRBS service is
not suspect relative to its budgets.

On the SS-CAS/GB-DABS interrogation link
(downlink), the chip width is reduced from the ATCRBS
0.8 µs to 0.25 µs to meet the standard DABS transponder
reception format. This 5 dB loss, together with the
19.5 dB decrease in antenna gain, results in a 24.5 dB
loss that has to be made up. The use of DPSK modulation
versus PAM gains back 6 dB, while the increase of power
adds an additional 10 dB. Finally, each data bit is
transmitted by a 7-chip Barker sequence (+8.5 dB),
with the result that the GB-DABS downlink is equivalent
to the ATCRBS downlink.

With respect to transmission by GB-DABS
(uplink), more power and wider pulses are used. The
power is increased by 10 dB to 1.25 KW from the nominal
125 watts which transponders operating above 12,500
feet are required to have. Alternatively, a two-level
whisper-shout power program using levels that differ
by 8-10 dB could be used. The whisper level will
lessen interference when near the GB-DABS.

Modulation gain is recovered in two ways. The ATCRBS link uses PAM off-on keying with 0.45 μs pulses. GB-DABS transmits at the DABS 1090 MHz data rate of 1 MHz using a 1 μs pulse period. The modulation is PPM (a 0.5 μs pulse occupies either the first or second half of the slot). For equal peak power and data rate, the modulation formats have equivalent energy/bit and equivalent performance. In the present case, GB-DABS has a 3.5 dB advantage in net data bit width. This advantage is further increased by encoding each input bit into a 4 bit Barker code. This decreases the data rate to 0.25 MHz but gains 6 dB more energy per bit. The result is a link with energy per bit equal to the ATCRBS link.

The design of the data link required the introduction of coded sequences of DABS bits to obtain more energy per transmitted information bit than the normal DABS signals provide. In doing so, deviations from the normal data block format were required in order to ensure that the overall format looks like a DABS signal to the airborne transponder. The remainder of this section describes the message formats of the SS-CAS/GB-DABS links, in particular the data block

formats, by specifying the data to be included and the number of bits needed in each data field.

The DABS Interrogation, Reply and Data Block Formats are illustrated in Figure 2-4 [6]. An ATCRBS preamble is transmitted in the DABS interrogation to suppress ATCRBS users. This is followed by a DABS transmission which lasts not more than 29 μs (within the minimum suppression time of most ATCRBS transponders). The DABS reply is shown to have an 8.0 μs preamble and is designed to be easily distinguished from ATCRBS replies. This preamble can be used as a source of reply timing with up to one ATCRBS reply present while at the same time the false alarm rate, arising from multiple ATCRBS replies, can be kept very low.

The normal data block format has 16 control bits, 16 surveillance bits, 56 optional data message bits and 24 parity bits, for a total of either 56 or 112 bits on both the interrogation and reply transmissions. The discrete address is overlayed on (modulo-2 added to) the parity field.

DABS Interrogation

Example: Reply Data Block Waveform Corresponding to
Bit Sequence 0010...001 Sequence 0010...001

DABS Reply

16 Bits	16 Bits	56 Bits	24 Bits
Link Control Field	Surveillance Data Field	Standard Message Field (Optional)	Address/Parity Field

Normal Data Block Format (Interrogation and Reply)

Figure 2-4: Normal DABS Message Structures

The SS-CAS/GB-DABS interrogation and reply for...ats are described in Figure 2-5. It can be seen that in length, modulation, and structure, both the interrogation and reply are identical to DABS. The standard message field is included in all transmissions. Where these signals differ is in the data block formats, which are given in Figure 2-6.

The SS-CAS interrogation data block format contains a 28 chip Newman-Hoffman preamble, a 4 bit GB-DABS ID, a 4 bit SS-CAS ID and a 4 bit message field.

The preamble sequence is provided both for synchronization purposes and to identify the transmission as an interrogation of a GB-DABS transponder. ATCRBS transponders will ignore it, and during the all-DABS and transition phases, other airborne DABS transponders will ignore it because of parity failure in the decode.

The 4-bit GB-DABS ID block identifies the ground site being interrogated. SS-CAS knows this ID from previous receipt of a GB-DABS squitter which contains it. This is no handicap, as SS-CAS has no

PREAMBLE 3.5µs

2.0µs

P₁ 0.8µs   P₂ 0.8µs

0.5 0.5 0.25 µs

DATA BLOCK 29µs

SYNC PHASE REVERSAL

DATA BITS PHASE REVERSAL POSITIONS

SS-CAS Interrogation

PREAMBLE 8.0µs

0.0 0.5 1.0   3.5 4.5

DATA BLOCK 56 or 112µs

Bit 1 Bit 2 Bit 3 Bit 4   N-1 Bit N
1 0 1 0 1 0 1 0   1 0 1 0

8.0 9.0

0 0 1 0   0 0 1

Example: Reply Data Block Waveform Corresponding to
Bit Sequence 0010...001 Sequence 0010...001

DABS Reply

Figure 2-5: SS-CAS/GB-DABS Interrogation and Reply
Formats

2-31

SS-CAS INTERROGATION DATA BLOCK FORMAT

| 28 Chip Newman-Hoffman Preamble | 28 Chip/4 Bit GB-DABS ID | 28 Chip/4 Bit SS-CAS ID | 28 Chip/4 Bit Message Field |

GB-DABS REPLY DATA BLOCK FORMAT

| 16 Chip Newman-Hoffman Preamble | 8 Chip/2 Bit Message Mode Indicator | 16 Chip/4 Bit GB-DABS ID | 16 Chip/4 Bit SS-CAS ID | 56 Chip/14 Bit Message Field |

GB-DABS SQUITTER DATA BLOCK FORMAT

| 12 Chip Newman-Hoffman Preamble | 8 Chip/2 Bit Message Mode Indicator | 16 Chip/4 Bit GB-DABS ID | 8 Chip/2 Bit AICRBS ACP Count | 68 Chip/17 Bit GB-DABS Position Coordinate or PRP and W_R |

Figure 2-6: GB-DABS/SS-CAS Data Block Formats

need to interrogate any GB-DABS without having first
successfully decoded its squitter. Four bits suffice
for _locally_ unique site address. Global assignment of
GB-DABS addresses must be done so that no two sites
which could possibly be in view of any single aircraft
have the same address. A total of 16 sites can thus
be distinguished in any one locale. Should this number
prove insufficient, bits from the message field may be
"borrowed" for auxiliary address data.

The SS-CAS aircraft includes only 4 of its
address bits in the interrogation. While it certainly
is not impossible that two aircraft with the same
4-bit "SS-CAS address" could be interrogating a given
ground site, in the unlikely event that this does
occur other means will be available to SS-CAS to dis-
tinguish replies intended for it from those designated
for another aircraft (e.g., expected reply time).
Should air traffic densities increase to the point that
a 4-bit ID is dangerously ambiguous, an aircraft can
cycle through various 4-bit segments of its 24-bit ID
to generate a uniquely recognizable sequence of ID's.

The message field can be used for other
purposes beyond those presently designed for SS-CAS.

The GB-DABS reply data block format has a
16 chip Newman-Hoffman preamble, a 2 bit message mode
indicator, a 4 bit SS-CAS ID, a 4 bit GB-DABS ID, and
a 14 bit message field. The functions of the preamble
and the two ID's are as in the interrogation block
format. The message mode indicator identifies the
message as an interrogation reply, a squitter or an
ATC message. The message field is used even when the
transmission is not an ATC message. One use is to
uplink the transponder turn-around delay for the par-
ticular interrogation.

Since some of the GB-DABS interrogations are
used for ranging, knowledge of turn-around delay is
essential. The GB-DABS cannot use a fixed turn-around
time because of the lack of synchronization between
the SS-CAS interrogations of GB-DABS and the ATCRBS
transmit-receive cycle. GB-DABS cannot reply during
the ATCRBS listening interval, since the reply fre-
quency coincides with the ATCRBS downlink frequency,
1090 MHz. The message field of 15 bits has capacity
to spare for uplinking the turn-around time; 3 bits
should suffice for the purpose.

The GB-DABS squitter consists of a preamble, mode indicator, GB-DABS ID, ACP count, and a field containing either a position coordinate or some ATCRBS site parameters (PRF and W_R).

The functions of the preamble, mode indicator and GB-DABS have been explained. The ACP count and the position field are described in detail in the following paragraphs.

The ATCRBS reply processor uses an internally generated count, the ACP count (azimuth change pulse), to tag replies with the antenna position at the reply time. Since it is readily available at the ground site, it is used in the squitter to give beam position.

ACP is a 12 bit number which divides 360° into 4096 equal intervals (0.0879°/count). Because of constraints on the squitter time, ACP can be transmitted in fewer than 12 bits. Squitter occurs four times per rotation (roughly once per second) at the times when the beam passes through North, East, South, and West. If the squitter could occur at <u>exactly</u> those points, only 2 bits would be required for ACP. How-

ever, the squitter time cannot be tied that tightly
to the antenna position, for exactly the reason stated
in the discussion of GB-DABS reply time: the trans-
ponder cannot be permitted to transmit while the ATCRBS
1090 MHz receiver is enabled. The listening interval
is about 1 ms (100 mi maximum range), during which time
the antenna rotates about 0.09° (1 ACP count). This
represents the maximum angular deviation of the squitter
transmission from the designated azimuth in the all-
ATCRBS case. In the transition and all-DABS environment,
additional demands on channel time forced by the inter-
lace of DABS and ATCRBS blocks can engender larger
squitter deviations. It is shown in Section 3 that
the squitter delay need never exceed 2 ms in any case,
a deviation of only 1 or 2 counts. In the DABS/ATCRBS
case, the interrogation scheduler can anticipate the
channel allocation and schedule the squitter one count
early as well. Thus, the four possibilities (1 count
early, on time, 1 count late, 2 counts late) can be
encoded into 2 bits, which when combined with the 2
quadrant bits required to give NSEW yield the 4 bit
representation of ACP indicated in Figure 2-5.

Associated with each ATCRBS main beam posi-

tion squitter is a position/site parameter message. When the beam squitters North, the position field contains the altitude of the ATCRBS beacon. In a similar manner, latitude is transmitted with East and longitude with South. Both PRF and rotation rate W_R are given with the West squitter.

The 17 bit position field is more than adequate to contain all the required site data. Altitude, for example, is encoded in ATCRBS Mode C using only 12 bits (100 ft. increments). The latitude/longitude fields are sufficient to locate the site within a few tens of feet. PRF and W_R may be given in deviations from some nominal values (say 400 interrogations/second and 0.25 rotations/second). For PRF, the possible values may be serialized for coding. Included with the PRF are two bits which specify the type of interrogation sequence used at the site and whether the site is ATCRBS or DABS. These are assigned as follows:

00: ATCRBS, uniform sequence

01: DABS/ATCRBS*

_____

* The ATCRBS sequence at a DABS/ATCRBS site is always uniform.

2-37

10: ATCRBS, jittered sequence

11: ATCRBS, staggered sequence

Note that because of the position information
available in the GB-DABS squitter, SS-CAS can compute
range to a newly acquired ground site without inter-
rogation. SS-CAS knows its position relative to at
least one other site (the site to which it is replying),
and by listening to the squitter from that site, can
obtain absolute SS-CAS position. Range to another site
acquired by squitter can be computed directly from the
two beacon positions.

It is worthwhile to point out that some of
the site data which has been included in the squitter
format could be deduced by the SS-CAS aircraft. In
particular, this is true of the rotation rate, the PRF,
and the jitter/stagger sequence.

An initial estimate of the rotation rate can
be made by differencing two successive centermarks.
This estimate will be in error to the extent of the
aircraft's azimuth motion over the 4 s measurement
interval. As tracking commences and reliable azimuth

rate data builds up, the aircraft motion component can
be smoothed out. The processor which determines W_R
must be designed to accommodate the conflicting demands
of smoothing to eliminate both measurement noise and
aircraft dynamics and quick response to detect physical
changes in W_R due to wind, electro-mechanical phenomena
in the antenna, etc.

Measurement of PRF is easy for a uniformly
sequenced interrogator and can usually be accomplished
on one scan (10 to 20 interarrival times should be
available for averaging). The nominal PRF and phase
of the jittered sequence should also be relatively
easy to establish since the sequence is only of period
3 (of three consecutive interrogations, the second is
3 µs late, the third 3 µs early relative to the time
of the nominal PRP). It is expected that this could
be reliably determined in one scan. Continued tracking
of the arrival times would reveal any discrepancy in
the initial assessment. Detection of the staggered
sequence will be more time consuming, since it is of
period 8 and has a 2:1 variation in interpulse spacing.

Thus, although provision of the above-described
information in the squitter expedites track initiation
for own aircraft, the capacity is available for other
functions if deemed necessary. This exemplifies how
the SS-CAS concept has margin to accommodate new or
different requirements.

The message structures introduced for SS-CAS
purposes are identical to the DABS format, causing
minimal interference with ATCRBS. Looking forward to
the mixed surveillance or all-DABS environments, we
note that the data block format is very different but
should result in negligible impact on the DABS-only
user, since parity check failure will nearly always
cause rejection of the received message. The effect
of DABS on SS-CAS/GB-DABS should also be negligible
since the preamble code structures and Barker sequences
will protect the data link from DABS-caused false
alarms.

Finally, we note that the use of the Newman-
Hoffman and Barker sequences will require modification
of the SS-CAS/DABS transponder. However, these changes
can all be put into digital logic, thereby minimizing
the cost that these changes will bring about.

2.2.3   SS-CAS Avionics

The SS-CAS avionics is described in block
diagram form in Figure 2-7. Two receivers are used
on-board SS-CAS to simultaneously monitor replies on
both top and bottom antennas to ensure that it has not
missed any replies. Only one transmitter is required
since the SS-CAS aircraft can sequentially interrogate,
in either its active mode or when interrogating GB-
DABS, via the top and bottom antennas and still ensure
that all pertinent airspace has been covered.

The receivers need only be of the same sen-
sitivity as those on a non-SS-CAS DABS transponder,
since the P_2 pulse correlation requirement does not
exist in the all-ATCRBS environment (reference the
earlier discussion). The interrogator power is speci-
fied to be 1.25 kW, 10 dB above the minimum for a
100 mi ATCRBS interrogator. Airborne interrogators
of even greater output power have already been proven
in BCAS tests at NAFEC, indicating that no requirement
beyond the state-of-the-art is implied here.

In addition to the transmitter, receivers,
antenna switch and antennas, there is the DABS/ATCRBS
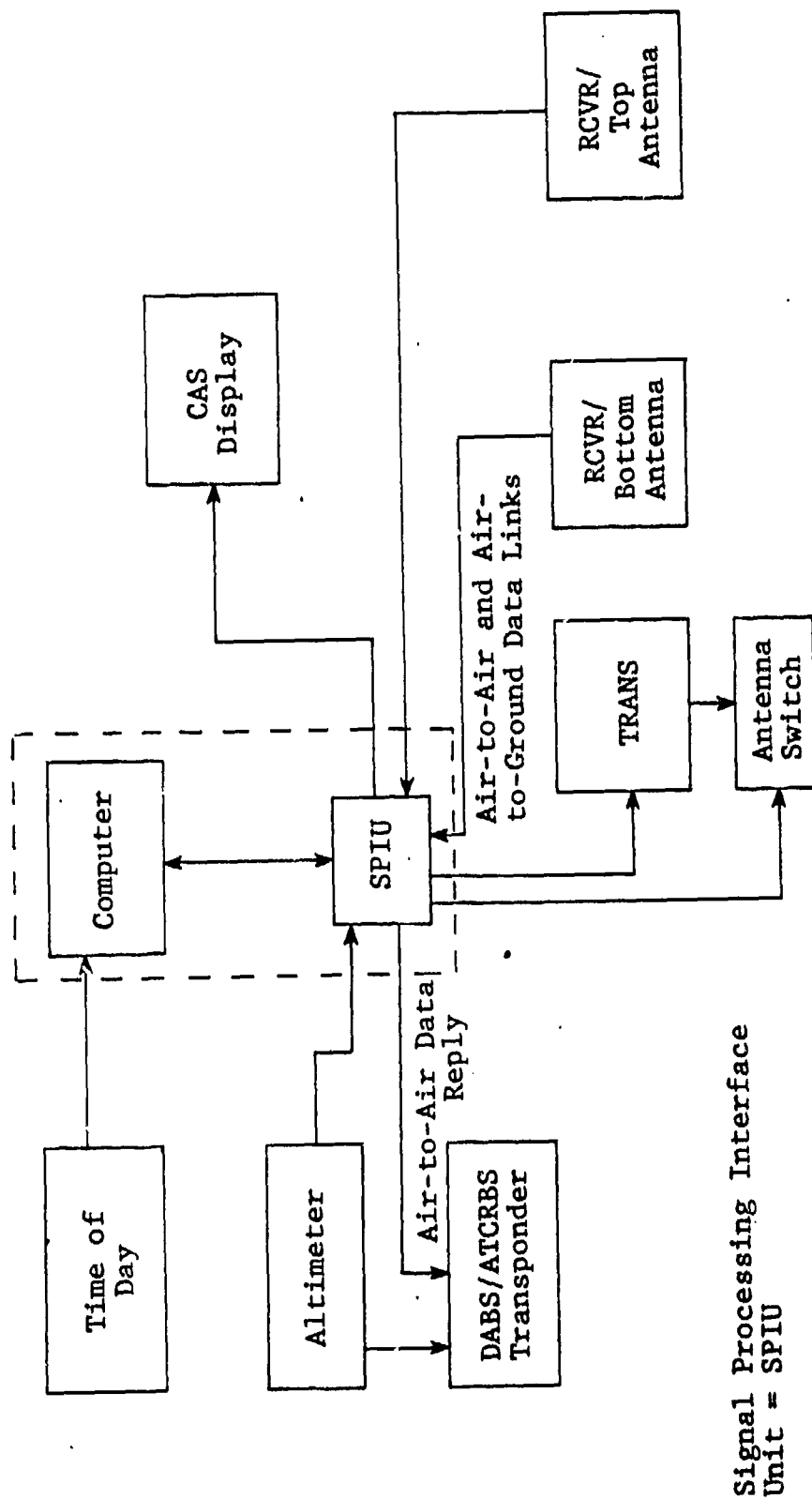
Figure 2-7: SS-CAS Avionics Configuration

Signal Processing Interface
Unit = SPIU

transponder, encoding altimeter, clock, CAS display,
computer and the signal processing interface unit
(SPIU) which interconnects all pieces of avionics
hardware with the computer.

The DABS/ATCRBS transponder is used in
SS-CAS for the ground-to-air squitter link and to
respond to other SS-CAS aircraft data inquiries. The
encoding altimeter provides the altitude reference for
computation of target relative altitude. The time of
day clock provides the timing base for all time of
arrival measurements. The computer includes software
for target acquisition, tracking and threat detection.
When a threat has been determined, a maneuver command
(based on whether the target aircraft is SS-CAS equipped
or not) is issued to the pilot via the CAS display.

2.2.4   SS-CAS Single Site Passive System Operation

Having been introduced to all the components
of the SS-CAS data gathering system, we now briefly
summarize the system concept for SS-CAS at a single
ATCRBS site. An aircraft initiates SS-CAS upon receipt

of a GB-DABS squitter. Once this has been accomplished,
the airborne unit interrogates GB-DABS at a once per
four second rate to determine R_1, the distance to the
ATCRBS interrogator site. In this manner, as dis-
cussed earlier, the information received on the squitter
together with the GB-DABS replies elicited by active
interrogation gives SS-CAS enough data to determine
target position from received replies. If we assume
initially that no two aircraft reply simultaneously,
then tracks for each can easily be formed. Squitters
from the target transponder will identify it as SS-CAS-
equipped. Finally, if the tracked target is determined
to be a threat and the threat is also an SS-CAS-equipped
aircraft, the intended maneuver is transmitted to the
other SS-CAS aircraft, and after the message receipt
is acknowledged, the maneuver command is displayed to
the pilot. For target threats which are not SS-CAS-
equipped, the maneuver command is displayed to the pilot
immediately following threat detection.

The story developed thus far in this section
has culminated in the presentation of a workable single
site passive solution to the CAS problem. Were it not
for synchronous garble, the story would be complete.

In regions of single ATCRBS site coverage, air traffic
densities will ordinarily be low enough that most
target replies will not be garbled. To resolve those
that are, the development of a unique tracker which can
read through garble with high reliability is underway.
The tracker exploits the temporal and spatial properties
of the ATCRBS reply runs, and the result serves to
complete the SS-CAS single site passive solution.

SS-CAS has available several optional aug-
mentations which can enhance or improve its performance
in environments which stress its capability. The
presence of more than one site can be used to advantage
in providing a choice of sites from which to track a
target or redundant tracks with completely different
garble environments. In addition, when severe garble
situations have been identified which cannot be resolved
by means of the tracker techniques to be presented,
there is the option to intermittently actively inter-
rogate, thereby garnering a set of replies with totally
different garble geometry which can be correlated with
the accumulated passive track data.

In the following two subsections, the tracker

and the multisite considerations for the ATCRBS
environment are presented.

2.2.5   The SS-CAS Tracker

        The key ATCRBS problem in SS-CAS tracking is
garble resolution. The passive garble problem is
illustrated in Figure 2-8. In both (a) and (b), two
aircraft are depicted which lie on a common radial from
an ATCRBS interrogator. The shaded area represents the
region in space (a hyperboloid of revolution) where
the replies from the two aircraft would partially over-
lap. The boundary of the region in a plane containing
the interrogator and the two aircraft is a hyperbola.
The distinction between (a) and (b) is that, in the
former case, the aircraft are separated by more than
the spatial length of a reply, whereas in the latter,
the spacing is less than a reply length. Consequently,
the garble region is larger for (b), and the SS-CAS
aircraft which is shown in both figures receives garbled
replies in (b) but not in (a). With the garble region,
the percentage of overlap will vary with position of
the receiver.
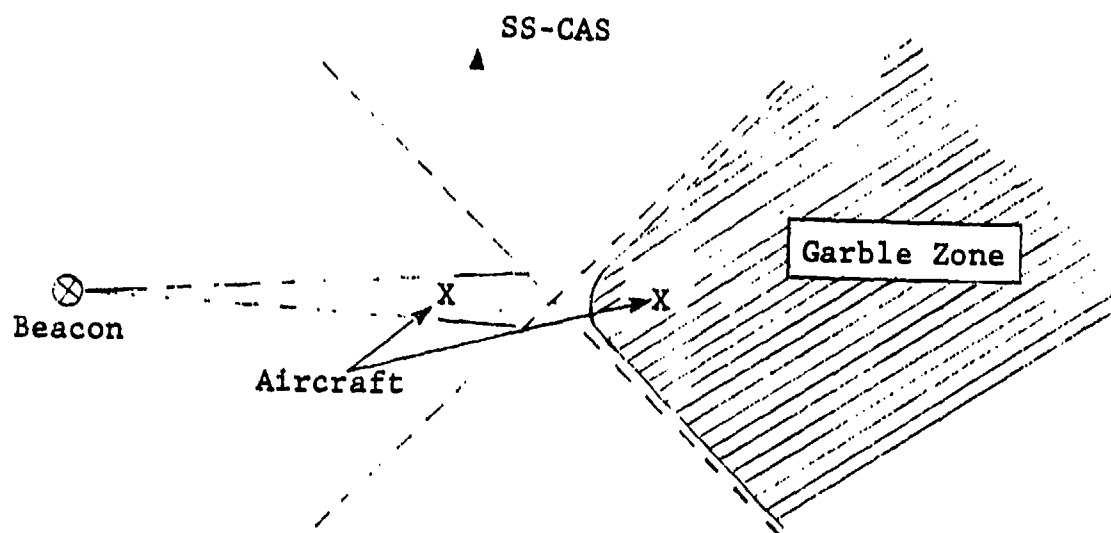
(a) Replies ungarbled at SS-CAS
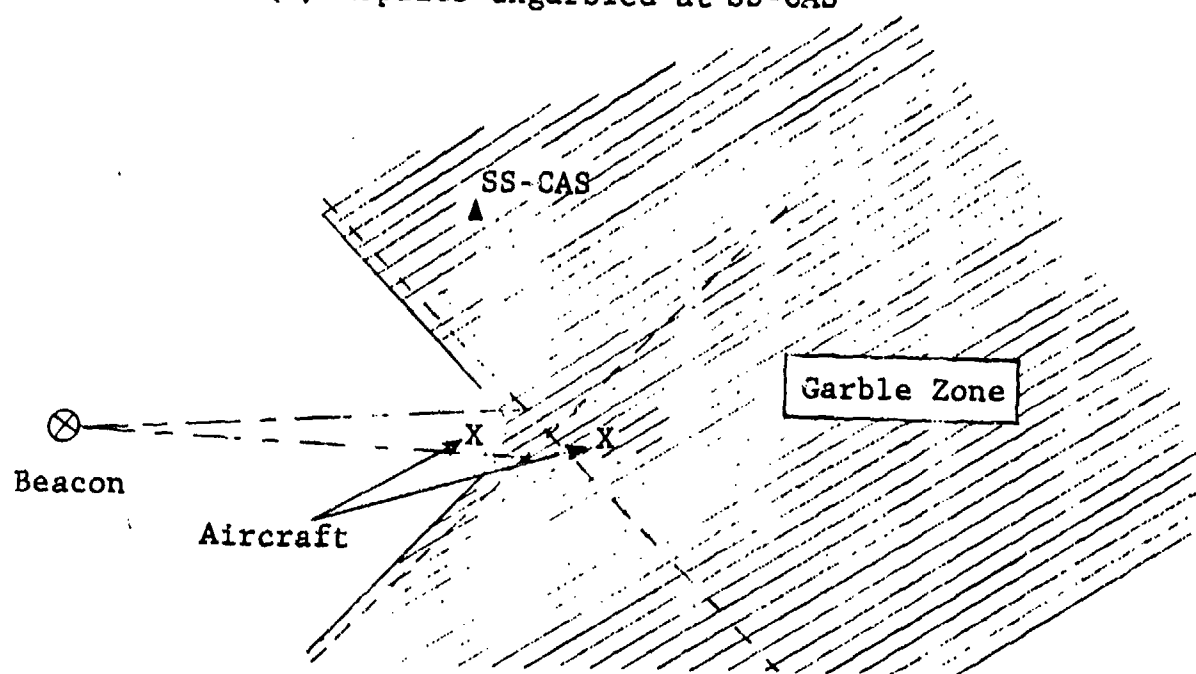
(b) Replies garbled at SS-CAS

Figure 2-8: ATCRBS Passive Synchronous Garble

The key principles used to resolve the garble problem are described below:

- The ATCRBS signal is modulated with on-off keyed PAM. That is, energy is transmitted for the "1" bits and no energy is transmitted for the "0" bits. A characteristic of this signaling is that interfering replies rarely destroy the "1" bits in a reply, but they may cause an error on "0"s. Since the "1"s are virtually certain to occur, SS-CAS will detect them.

- On the other hand, with high probability the "0" bits will often be detected as "1" bits in a garble environment. However, as aircraft motion shifts the overlapped replies relative to one another by as little as 0.5 μs (500 ft change in differential range), successive samples of a track will greatly increase the probability that a true code can be read. Thus, given enough time, one can hope to resolve ambiguities, eliminate all phantom tracks and determine all true tracks.

- Targets with overlapping interrogation replies at the SS-CAS aircraft are nearly always separable in azimuth

2-48

since no two targets will garble at the
SS-CAS aircraft on all of each other's
ATCRBS replies per scan unless their
positions in space are identical except
for altitude. Thus, with a high prob-
ability, azimuthal "end effects" will
provide some clear altitude and ID
target replies, even when most of the
replies per scan per target are over-
lapped, allowing azimuthal centermarking
of targets.

The end effect is illustrated in Figure 2-9.
There a two-dimensional array is shown in which the
ordinate is the differential time of arrival and the
abscissa is the interrogation sweep number per scan.
A given row then represents a constant value of ΔTOA.
In the top row shown, replies occur without overlap
between aircraft interrogations 3 and 18 inclusive.
The centermarking of this aircraft is then a trivial
problem. In the second row two overlapping reply runs
are shown. However, thanks to end effects, it is easy
to determine aircraft identity, altitude and azimuth
centermark of each. This is the case since "1"s are
rarely destroyed and overlaps merely "fill in" "0"s.
Thus, with very high probability, returns 4 through 17
will have no "0" for all ID and altitude replies which
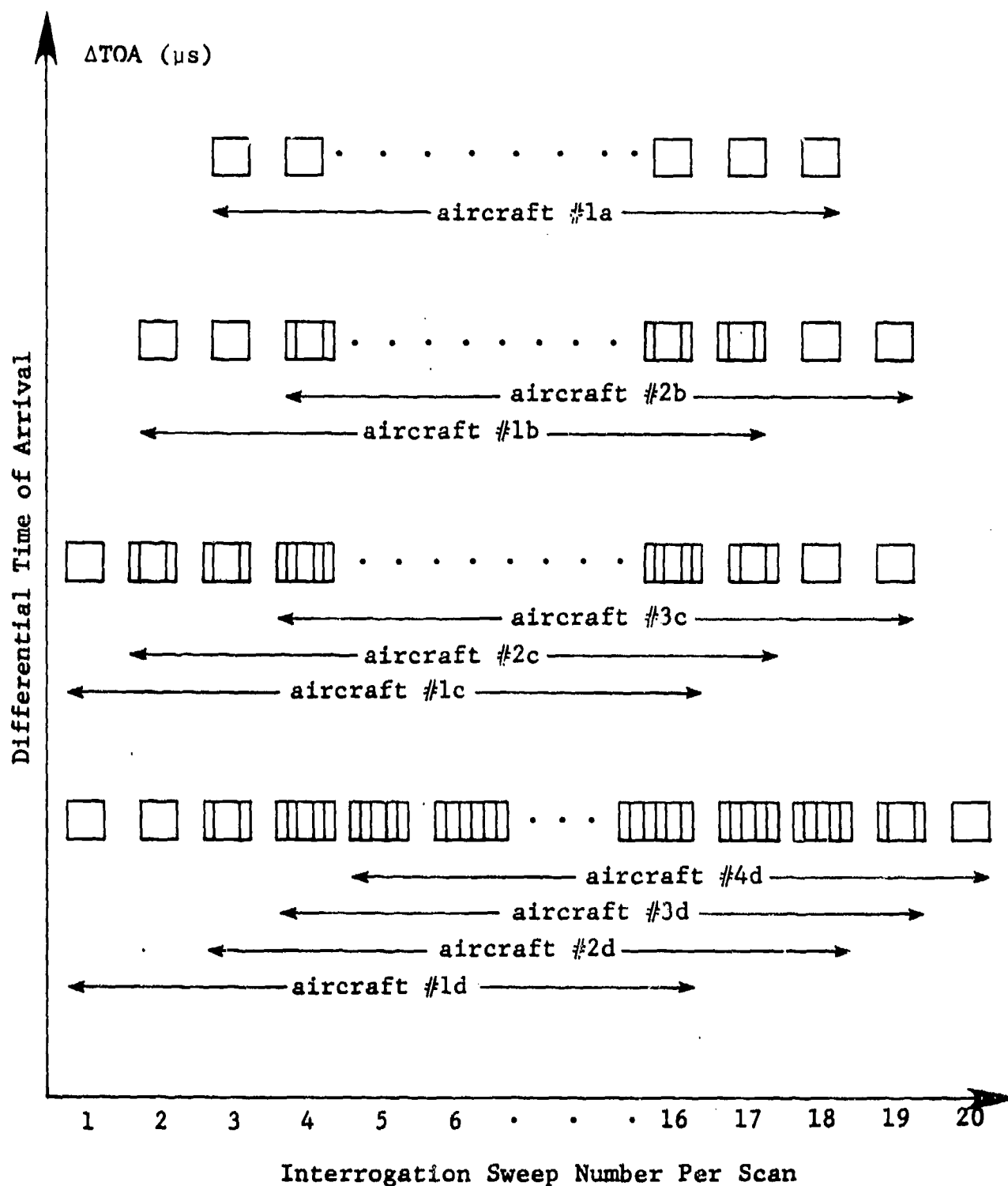
Figure 2-9: Obtaining Track Information from Garbled Replies

is not in each of the ungarbled aircraft 1 and aircraft 2 replies.

The third row describes a case of a three-aircraft overlap. Clear end effects exist for aircraft 1c and 3c, but the aircraft 2c reply run is completely garbled. However, a study of the bit patterns of each of the replies could allow a clear azimuth centermarking for aircraft 2c.

A four-garble situation is illustrated in row d, and even though aircraft 3d and 2d have no clear end effects, transitions in the density of the "1"s and "0"s are present which at least theoretically permit the centermarking of all four aircraft.

A simple model for ATCRBS replies which can be exploited for garble resolution is the following. Suppose that "1"s and "0"s are equiprobably and independently distributed in a reply. Idealize the garbling properties to the extent that "1"s are never garbled, and that a "1" + "0" overlap always results in a "1". Then the probability of a detected "0" in a region of N overlaps in 2^{-N}, and correspondingly, "1"s occur

with probability $1-2^{-N}$. The sample statistics of "1"s and "0"s could be used to estimate N at various points in the reply run, but this procedure quickly reaches diminishing returns since the number of bits/reply is not large. However, distinguishing among "0"s of probability 1/2, 1/4 and 1/8 (i.e., zero, one or two overlaps) is certainly possible. These principles will be incorporated into the ATCRBS target tracker design.

What has been illustrated is not a complete set of all garble situations. However, it is sufficient to illustrate the principle of utilizing azimuthal end effects to resolve garble ambiguities.

Most passive garble problems originate with aircraft at differing ranges from SS-CAS. Figure 2-10 helps illustrate the point. In this figure, the passive garble geometry is depicted from a different point of view than that of Figure 2-8. Here, the interrogator and SS-CAS positions are fixed, and the locus of garbling aircraft is varied. The ellipse shown is a locus for aircraft, all of whose replies would arrive at SS-CAS with the same delay relative to the interrogation time. The beacon and the SS-CAS aircraft
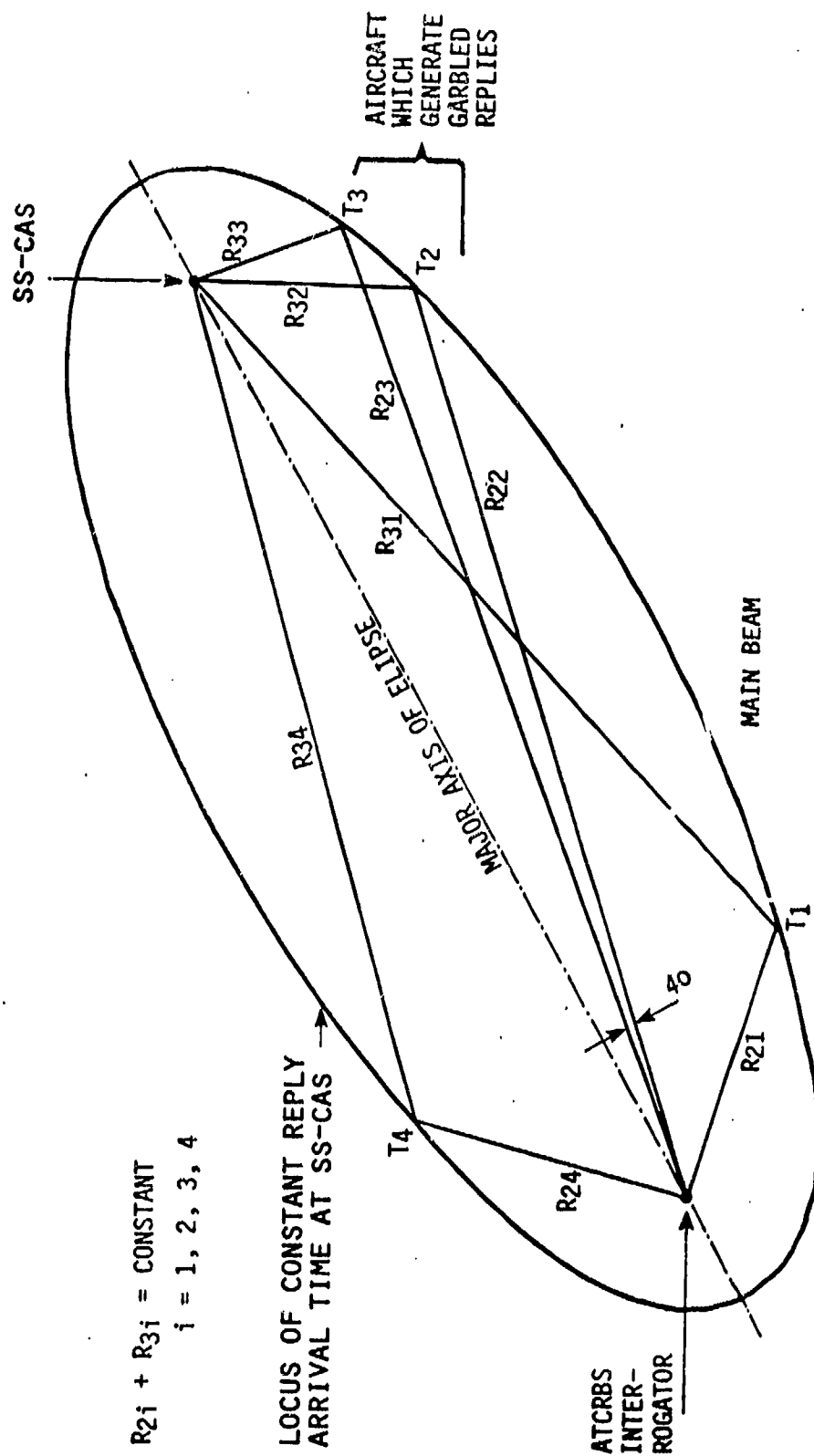
Figure 2-10: Geometry of Passive Synchronous Garble for Fixed Interrogator, Fixed Receiver

are the foci of the ellipse. Since ATCRBS interrogations are highly directional, not all positions on the ellipse correspond to aircraft which would actually respond to one interrogation.

In the figure, aircraft T_2 and T_3 are shown within an ATCRBS beamwidth and would have fully overlapping replies at SS-CAS in response to an ATCRBS interrogation. Note that their ranges from SS-CAS, R_{32} and R_{33}, are not equal, however. Thus, if T_2 and T_3 were interrogated by SS-CAS, a new garble environment would occur. In general, if an active mode omnidirectional interrogation is used by SS-CAS following passive garble detection, new garble resolution information can be obtained. This information can, in some geometries, enhance garble resolution of existing tracks, especially in moderate traffic density areas.

Using all the principles discussed thus far, the SS-CAS tracker can acquire aircraft sufficiently far away that at least 70 seconds are available before a collision hazard could occur -- 40 seconds is used to establish track reliability and 30 seconds is for

escape maneuvers. Thus, by allowing extra tracking time, SS-CAS is able to acquire aircraft in garble and to continue tracking through it.

A block diagram description of the tracker is given in Figure 2-11. After reception of a declared time of arrival (a bracket pair spread 20.3 μs apart) the ΔTOA is computed and the value of ΔTOA is passed to the centermarker ($\Delta \Psi$), altitude and ID estimates. In this subroutine a two-dimensional array, as described in Figure 2-9, is generated, and for each row of the array (constant ΔTOA) clusters of replies corresponding to a sequence of replies from at least one aircraft are seen. For each cluster that it finds, the bit pattern of each reply is studied to determine the reply which has the greatest number of zeros. Starting with this reply, it then proceeds to make an estimate of the azimuth (centermark), the altitude and the ID for each aircraft it determines to be part of the cluster. In addition, it associates with each centermark, altitude and ID a confidence factor which is a function of the contiguousness of the cluster, or the percentage of zeros in the "best" reply, which in turn is directly related to the reply rate probability

2-55
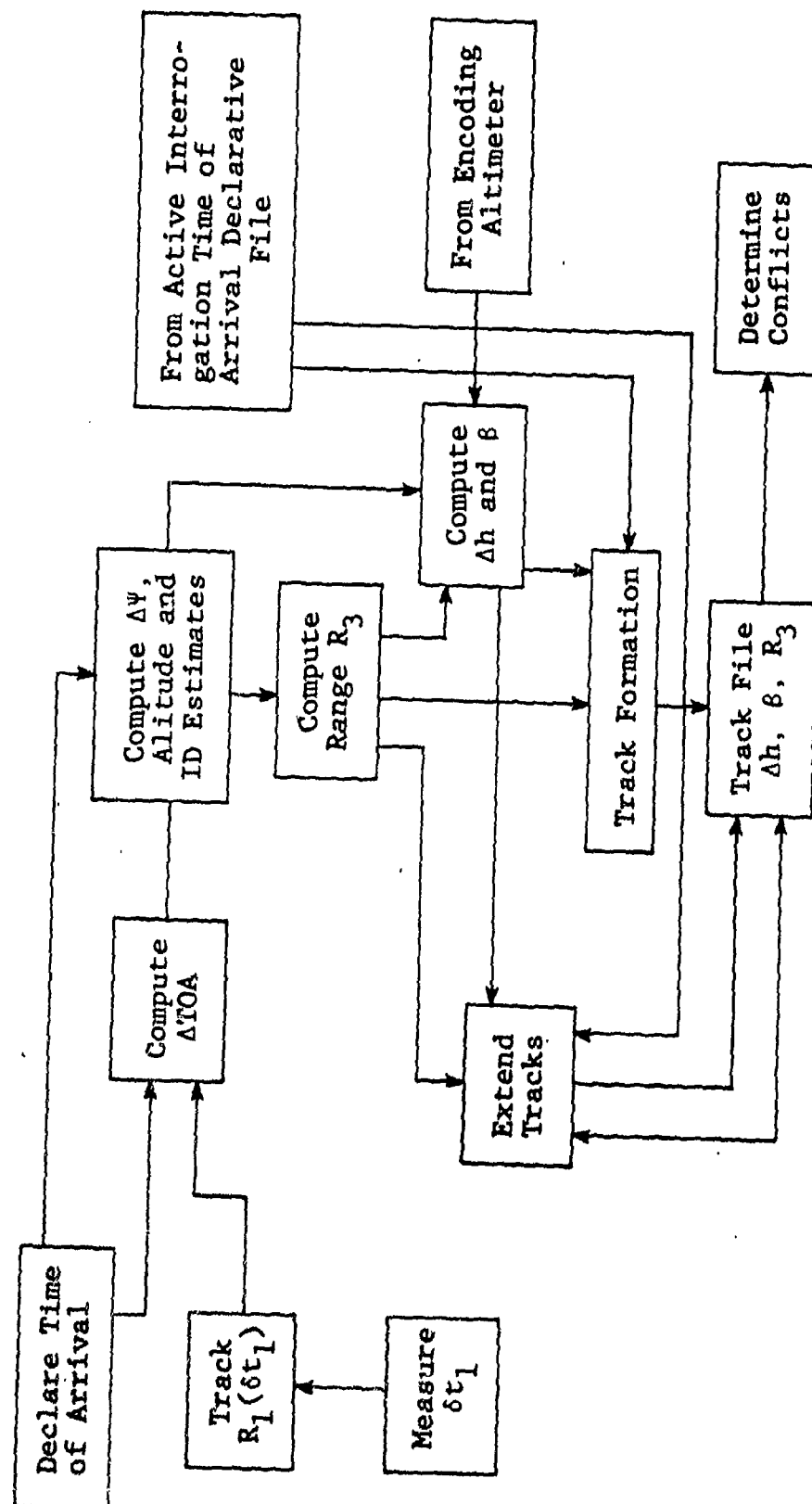
Figure 2-11: SS-CAS Tracker

2-56

for ATCRBS and the "end effect" properties observed in the cluster. Once these estimates are made the range R_3 can be computed. The range R_3, altitude estimate, $\Delta\Psi$ estimate, and ID estimate are then passed on to the relative altitude and bearing computation subroutines.

The computed values of R_3, Δh and β, along with the confidence factor for the computation, are sent on to the extended track file where previously formed tracks are correlated with the latest scan target estimates. Those replies which correlate highly are then used to extend existing tracks, while the remaining target estimates are sent to the track formation routine.

In track formation, tracks are formed by straight line estimates over a 3-scan period. Taking into consideration aircraft dynamics, a single target (Δh, R_3 and β) estimate per scan can be used in the formation of more than one track. This comes about since we do not have perfect information and want to ensure against losing true tracks. False tracks (or phantom tracks) will be eliminated in track extension when with time the true "O"s of a target reply become evident.

2-57

Active mode interrogation replies are correlated with existing tracks in the track extension file. Those which correlate in range and have at least the same "O"s as the targets in the track file are used to improve the confidence factor on the track.

The remaining replies are then correlated with those in the track formation file. If a reply correlates well in range and has at least the same "O"s as the tracks in correlation, then this reply is used to improve the confidence factor of the track in formation. All other active replies which do not correlate with passive tracks in formation or in extension are then simply eliminated. Thus, active mode replies are not tracked but are used to improve our confidence in target tracks in the passive track file.

With time, aircraft dynamics will allow the tracker to see the true "O"s, and the confidence in R_3, Δh and β will improve on real tracks, while phantom target tracks are eventually purged from the track file before the target ever comes within range of being considered a potential threat.

2.3   SS-CAS in a High Traffic Density, Multiple
           ATCRBS Site Environment

As the density of aircraft increases, the
number of ATCRBS sites within a 100 mile radius in-
creases, reaching its limit (greatest density/largest
number of ATCRBS sites per unit area) in the Los Angeles
Basin. If we look at the high density air space, we
can state the following:

- The so-called "N^2" garble problem in
  an all-active mode becomes so severe
  in high densities that it will not
  help to utilize the active mode to
  improve the confidence of passively
  formed tracks.

- The passive garble problem itself is
  more severe per site due to the higher
  density of aircraft and the increased
  probability of time arrival overlap.

- When there are several ATCRBS sites in
  a given area, SS-CAS can select sites
  from which to track so that the synchro-
  nous garble environment created by one
  site is essentially independent of the
  synchronous garble from others, as is
  illustrated in Figure 2-12. This

SITE B

SITE B REPLIES FROM
①, ②, and ③
DO NOT OVERLAP AT SS-CAS

REPLIES FROM AIRCRAFT
WITHIN DASHED LINES
OVERLAP AT SS-CAS

4° MAINBEAM

X
SITE A

SS-CAS

REPLIES   REPLIES   REPLIES
FROM ①   FROM ②   FROM ③
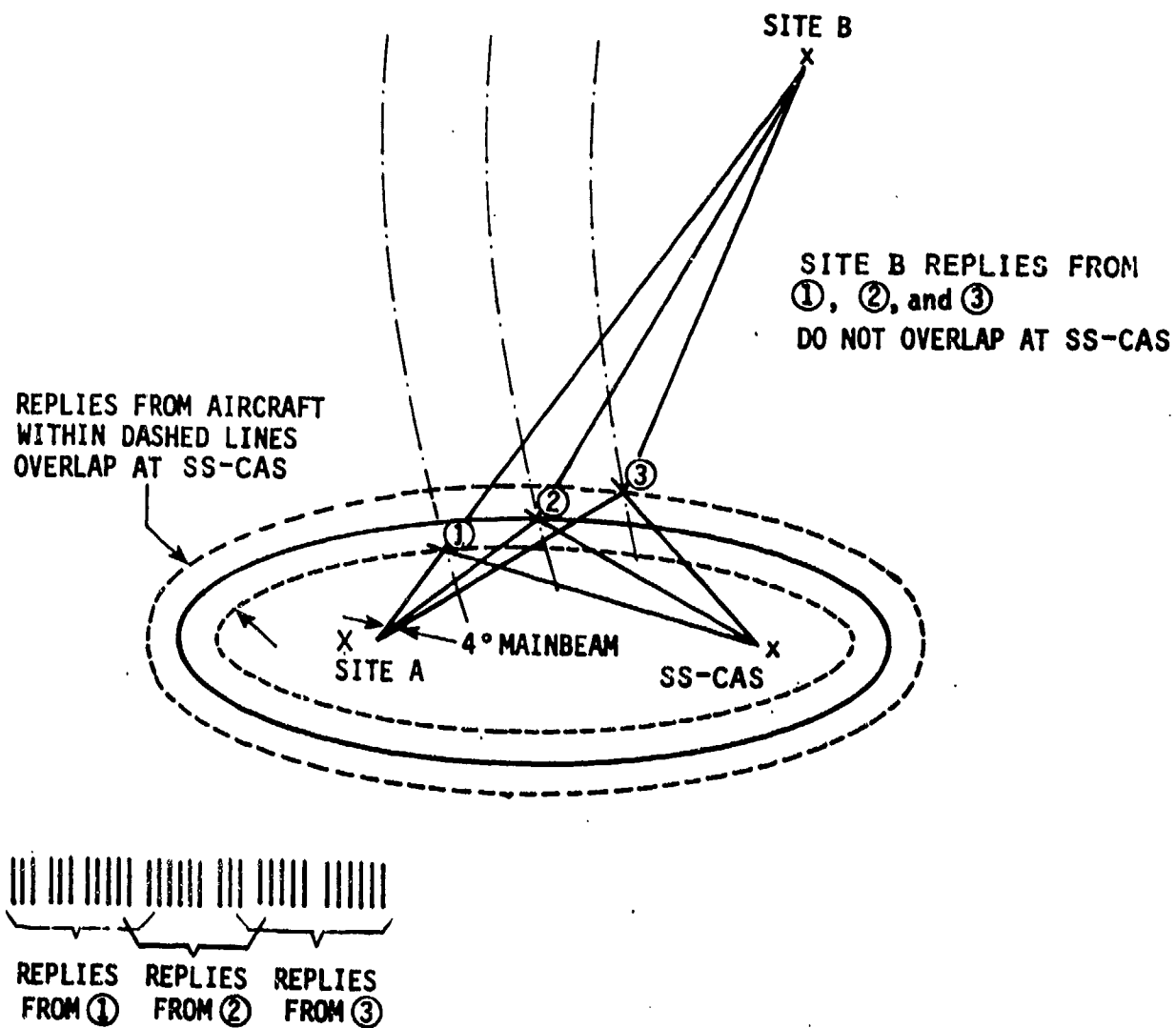
FIGURE 2-12   MULTI-SITE RESOLUTION OF GARBLE

provides the BCAS tracker the option of
utilizing additional ground sites.

- Additional ground sites will not only
  ameliorate synchronous garble problems
  of a particular site, but their use can
  also provide a faster update rate to
  a tracker which can coordinate target
  replies to as many as four ATCRBS
  interrogators.

Based on these principles, SS-CAS could
operate in the following manner in a high aircraft
density multi-site environment. An SS-CAS aircraft
entering such a region listens for GB-DABS squitter
and interrogates each site it hears. Given the multiple
GB-DABS replies, SS-CAS determines its own position and
selects the four sites that will provide the best
geometry for obtaining independence among the target
replies to the several ground sites.

Replies for each selected site are utilized
in forming and extending tracks. When the BCAS aircraft
is in the ATCRBS main beam ($\pm 2^{\circ}$ azimuth region) target
replies can be very heavily garbled. To resolve the
impact of such garble, main beam TOAs (the $\pm 2^{\circ}$ region)

2-61

of any particular site would not be used by the tracker
when they appear to be heavily garbled. This region of
space would still be covered by the other three selected
sites so that aircraft in all airspace in the vicinity
of SS-CAS will be tracked.

Between the extremes of single site ATCRBS
coverage and the high density multi-site environment,
there are environments in which fewer than four ATCRBS
sites are usable. Assuming that low site density is
reasonably well correlated with low traffic density,
the occasional use of active mode in such an environ-
ment to resolve a passive garble problem will have
lesser impact upon the remaining ATCRBS environment
than in the full multi-site case.

3.　　　　　SS-CAS IN THE ALL-DABS ENVIRONMENT

In the all-DABS environment, each aircraft
carries at least a DABS transponder capable of
responding to both DABS and ATCRBS interrogations.
Many aircraft will, in addition, be SS-CAS equipped.
As in the all-ATCRBS environment, the ground site
is equipped with a GB-DABS transponder which functions
for ranging and data link as described previously.

A key element of SS-CAS design in the all-
DABS environment is that in the vicinity of a single
DABS site it can operate without the synchronous
garble problem found in ATCRBS. This is achieved
because:

> i)　　DABS interrogations are uniquely
> addressed to an intended recipient and
> will be ignored (no reply issued) by
> other aircraft; and

> ii)　　The DABS scheduler makes up its roll
> call based on knowledge of the range
> and azimuth coordinates of all aircraft
> and can control the interrogation and
> reply times so that the replies used

for CAS purposes do not overlap anywhere
in space.

The tracker requirements are greatly simplified as a
result. Other important features are: (i) the avail-
ability of the DABS data link and (ii) the fact that
more favorable measurement geometry can be achieved
by exploiting synchronous features of the interroga-
tion scheduling.

Each of these key factors will be explored
in some depth as they arise in the description. This
will occasionally necessitate interruptions in the
concept flow so that elements of DABS, upon which the
SS-CAS concept heavily depends, can be discussed.

3.1   SS-CAS in Regions of No Surveillance

3.1.1   Over Ocean Mode

The discussion required here almost parallels
that in the corresponding ATCRBS section (2.1) and can
be handled briefly. The only new possibility that

3-2

arises is that the target can now be a non-SS-CAS
equipped DABS aircraft.

Since there are no ground sites in view,
SS-CAS operates actively. If a squitter from a non-
SS-CAS* DABS aircraft is received, SS-CAS begins to
interrogate that aircraft at a 1 second update per-
iod.** When there is more than one reception, each
squittering aircraft is interrogated separately.
Since there will be few nearby aircraft, there is no
problem in scheduling the interrogations to avoid
reply garble. Targets are tracked in range (measured
by the round trip interrogation/reply interval) and
altitude (decoded from reply). Tracking is substan-
tially simpler than in the (garbled) ATCRBS case.

If a non-SS-CAS threat is detected, the
SS-CAS aircraft can determine its own evasion maneuver

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*   The DABS reply contains a "capability field" which
is a 6-bit portion describing the avionics equipment
that it carries.

**   In order for a DABS aircraft to determine whether
it is being interrogated by a ground site or an
SS-CAS aircraft, one DABS address bit will be
reserved to identify SS-CAS interrogators.

and, if the target is suitably equipped, can use the
DABS data link to simply inform the target aircraft
to maneuver. Since message receipt by the target will
be acknowledged in its reply, the integrity of col-
lision avoidance service is very high in this mode.

3.1.2   Pop-up Targets

As in the all-ATCRBS environment, some low
altitude targets may occasionally be out of radar
coverage. In contrast to the ATCRBS case, these targets
are passively detectable by SS-CAS because of the
transponder squitter. When a squitter is received,
it can be checked for ID match with targets in the
track file. If the ID is new, a track should be
initiated.

Squitter-detected targets can be interrogated
for preliminary altitude and range estimates. Targets
lying inside certain relative altitude, range, or range
rate limits can be tracked actively by discrete inter-
rogation once per second. The number of such targets
should be small and pose no burden to the airborne

interrogator, just as in the over-ocean case. Further-more, an aircraft is unlikely to remain in a coverage gap for long; it may be on final approach (ultimately of no interest), taking off (about to enter coverage) or passing through either a coverage gap or sector hand-off. Failure of a DABS sensor could, of course, prolong the lockout period, although the DABS network management function should rapidly reassign primary and secondary coverage responsibilities of the adjacent sensors.

The significant advantages in the all-DABS approach to out-of-coverage targets are that (i) they can be detected at more distant range than in the all-ATCRBS case, lessening the possibility of pop-up, and (ii) they are interrogated more often without engender-ing synchronous garble, enabling quicker and more reliable threat detection.

3.2   SS-CAS in a Low Traffic Density, Single
           DABS Site Environment

In the vicinity of a single DABS site, the SS-CAS aircraft operates almost entirely passively

[6,7]. By listening to both DABS replies and the squitter from the DABS transponder colocated with the interrogator, SS-CAS can obtain its own position and that of the target once per passage of the main beam (approximately 4 seconds). Active use is restricted to intermittently interrogating another aircraft whose replies are being garbled by DABS or ATCRBS fruit (replies to an adjacent site) and to interrogating the GB-DABS for ranging.

The subsections which follow provide the details of how SS-CAS operates in the DABS environment. The first section (3.2.1) explains the interrogation scheduling procedure used at a DABS/ATCRBS site. Section 3.2.2 presents two options for position measurement and explains each fully. These differ in that Option I utilizes ground-derived surveillance data uplinked to the aircraft via the data link portion of synchronous DABS interrogations. Option II is transparent to the ground system but places a greater burden upon the SS-CAS avionics. Tracker and multi-site considerations are discussed in the final subsections (3.2.3 and 3.2.4).

3.2.1   DABS Channel Management

In order to understand the measurement pro-
cedure, it is necessary to first explain the schedul-
ing of functions at a DABS/ATCRBS site. Figure 3-1
illustrates the allocation of time at the interrogator.
Time is partitioned into blocks (or periods) whose
length equals one-half the ATCRBS PRP for the site.[*]
If, for example, PRP = 400 pulses/sec, the block
length is 1250 µs.   Blocks alternate between DABS
and ATCRBS service.

Two types of DABS interrogation formats
must be employed when both CAS services and DABS sur-
veillance are desired, and these are used on alternate
DABS blocks.   The first is called a surveillance
block, the second is a synchronous block.

In a surveillance period, aircraft inter-
rogations and replies (an interrogation-reply pair is
called a transaction) are scheduled into groups called

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[*] ATCRBS interrogations are never jittered or stag-
     gered at a DABS/ATCRBS site.
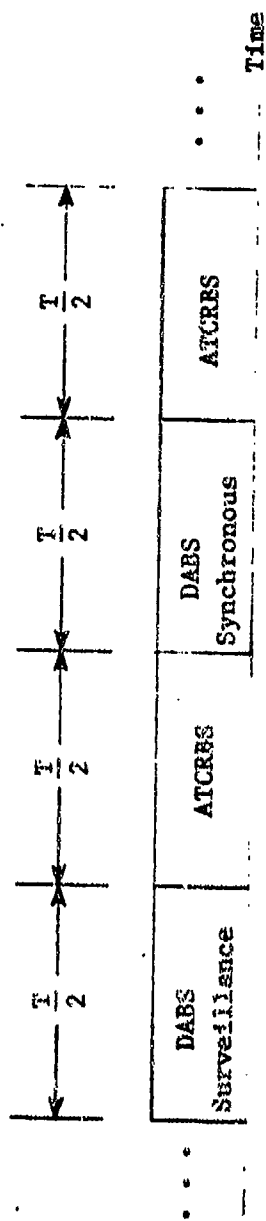
Figure 3-1: Channel Allocation at a DABS/ATCRBS Site

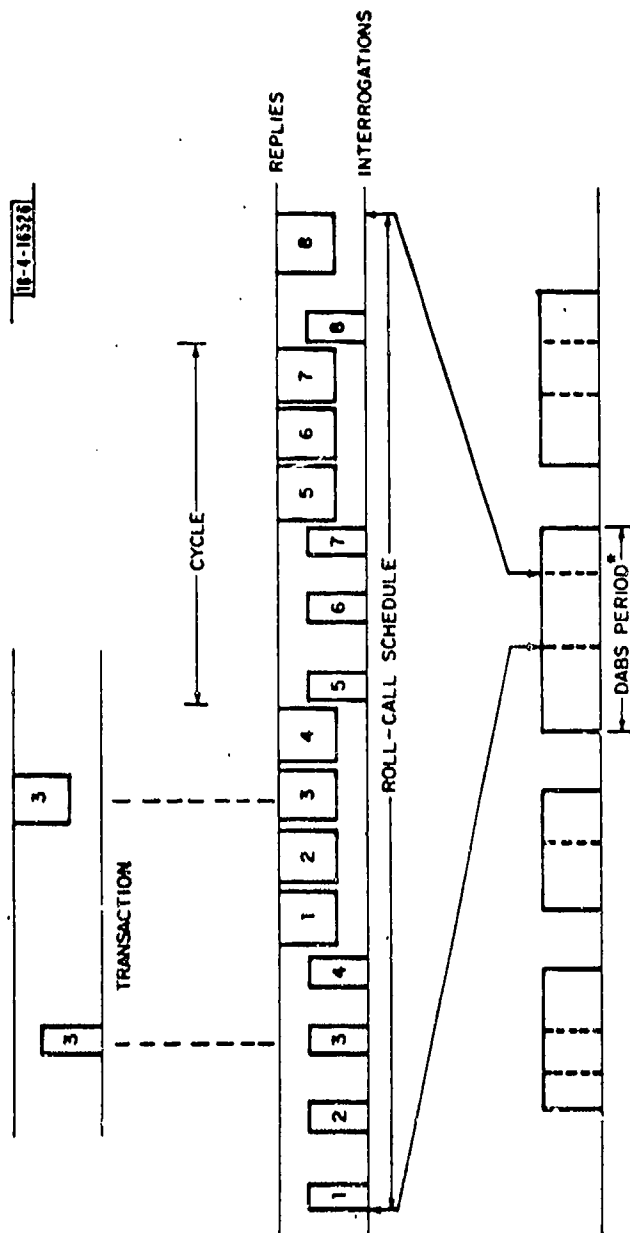| DABS Surveillance	ATCRBS	DABS Synchronous	ATCRBS
$\frac{T}{2}$	$\frac{T}{2}$	$\frac{T}{2}$	$\frac{T}{2}$

Time

T = ATCRBS PRP

cycles, which consist of a set of interrogations
followed by the replies to those interrogations (see
Figure 3-2, from Drouilhet, Reference 6). A cycle
terminates when the next scheduled interrogation would
overlap the expected arrival time of the first reply
in the cycle. A DABS block can, as shown, consist of
several cycles. The interrogations are arranged in
increasing range order (nearest-in first) in such a
way that the replies will not overlap at the inter-
rogator (although they may overlap at other points in
space), thus eliminating synchronous garble from the
interrogator's standpoint. At the ground, these
replies are processed for surveillance updates on the
interrogated craft; range and azimuth are measured
and altitude decoded from the reply.

The format of the synchronous block is an
extension of a concept developed by Amlie (Reference 9)
under the name of "Synchro-DABS". His idea of synchronous
interrogation is to time the interrogations of several
aircraft all lying in one DABS beam in such a way
that they all issue replies simultaneously. The reply
instant is denoted as T_o and occurs at the center of
the DABS block (see Figure 3-3).

3-9
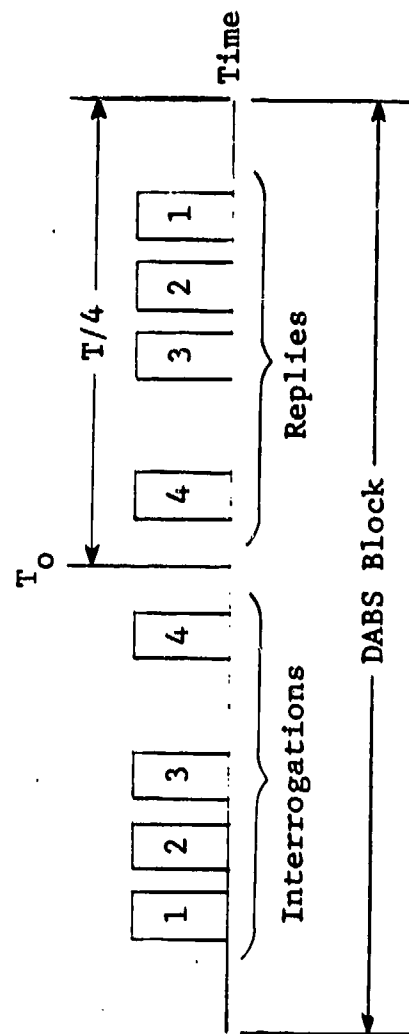
Figure 3-2:   DABS Surveillance Block

Figure 3-3: Synchronous Interrogations in "Synchro-DABS"

Synchronous interrogations must be scheduled
in a manner that ensures that the replies will not
overlap at the beacon. This is accomplished by select-
ing for interrogation a set of aircraft within the beam
having the property that the radial spacing between
each aircraft in the set exceeds the spatial length,
L_r, of the reply ($L_r = cT_r$, where T_r = duration of
reply). This guarantees garble freedom of the replies
at the DABS sensor. Aircraft are interrogated in
reverse range order (most distant first), with the time
separation between interrogations equal to the range
delay between aircraft. This method does not, how-
ever, assure garble freedom for receivers at other
positions in space, as the example in Figure 3-4 shows.

Garble freedom in all of space can be assured
by delaying the response from the latter of two inter-
rogated aircraft until the trailing edge of the wave-
front of the reply from the former has passed the
latter, and so on. No aircraft replies until all the
replies of the more distant (from the site) aircraft
have passed it. In this manner, the expanding spheri-
cal shells containing each reply never intersect at
any one point in space, providing complete garble

3-12
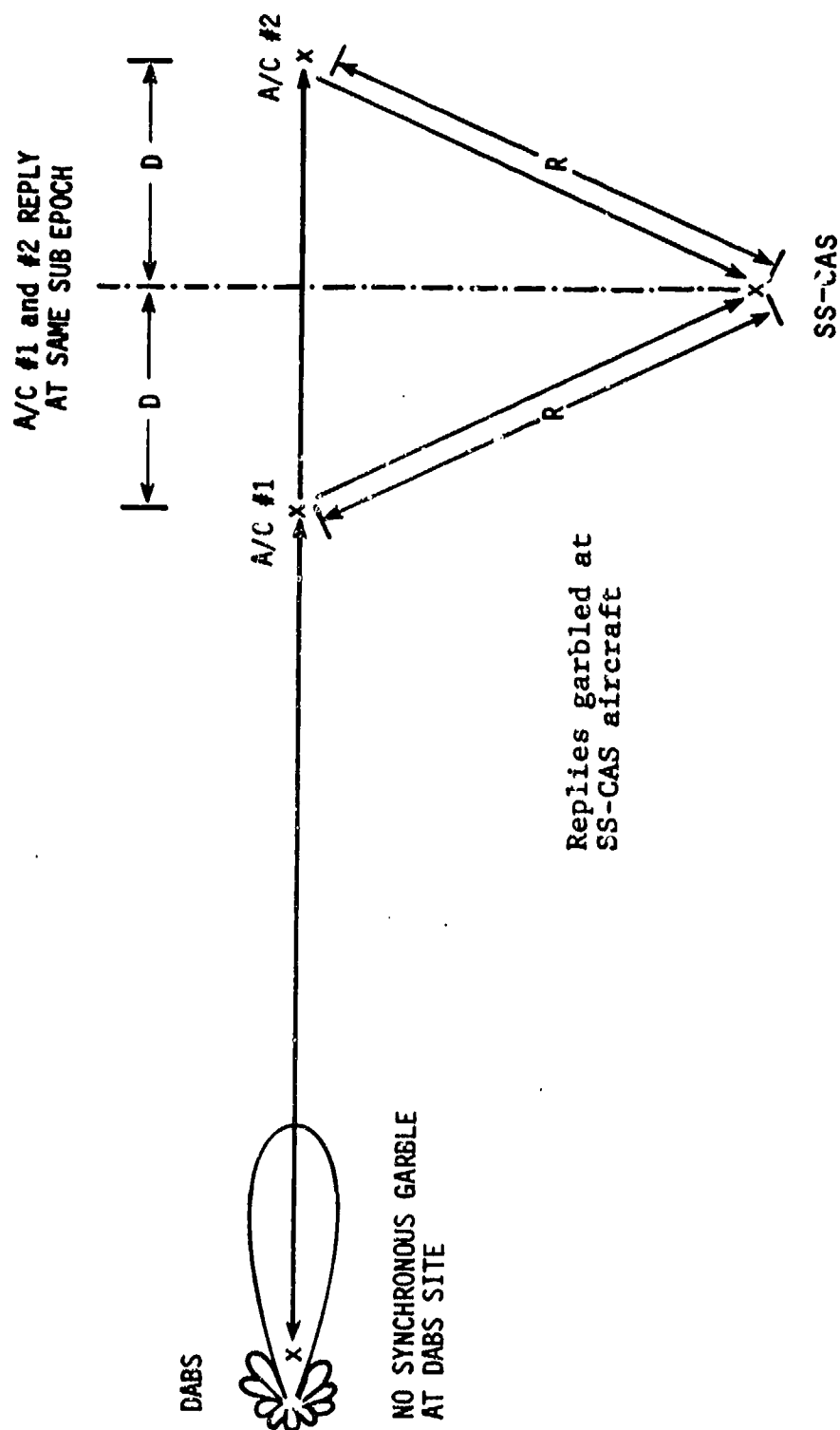
Figure 3-4: Illustration of Synchronous Garble at SS-CAS Using Synchro-DABS Interrogators

freedom. Figure 3-5 shows the reply sequence and a two-dimensional picture of the resulting wavefronts. Interrogations so ordered are called synchronous in the remainder of this report.

The reply times are under ground control, since the interrogator knows the range of each aircraft in the roll call. Reply time is encoded in the interrogation in a 6 bit "epoch field". The least significant bit in this field is called the subepoch and represents a 16 μs delay. The reply time will be $T_O + (16k)$ μs, $0 \leq k \leq 63$. The epoch field is included in the reply as well so that any receiver detecting the reply can tell when it was transmitted relative to T_O. If desired, the azimuth and range measured on the previous surveillance call can be included in the message field of the synchronous interrogation. Application of this idea is found in one of the position measurement options to be discussed.

To summarize, the DABS/ATCRBS sensor sequences events as follows:
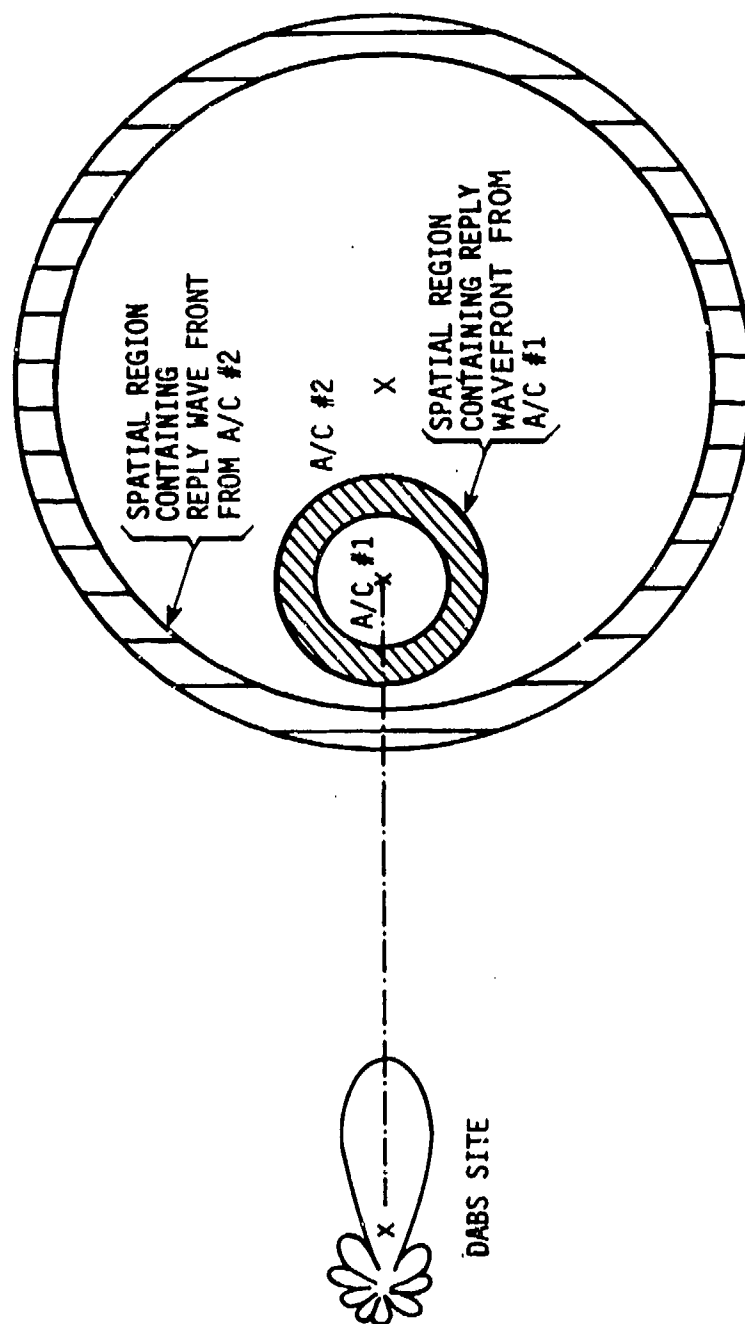
Figure 3-5: Illustration of Garble-Freedom in all Space Achieved
with DABS Synchronous Interrogations

1) DABS Surveillance Block

   Interrogations are transmitted for
   surveillance; replies processed for
   range, azimuth and altitude.

2) ATCRBS Block

   ATCRBS interrogation is transmitted
   at the beginning of the block. ATCRBS
   replies processed for surveillance.

3) DABS Synchronous Block

   DABS synchronous interrogations are
   transmitted for CAS purposes. Inter-
   rogation schedule is based on position
   data obtained from previous DABS sur-
   veillance block. Replies are not
   processed for surveillance at the
   ground.

4) ATCRBS Block

   ATCRBS interrogation transmitted at the
   beginning of the block (a _fixed_ time
   after the T_o of the previous DABS block).
   ATCRBS replies processed for surveillance.
   The cycle repeats starting at 1).

Each DABS aircraft is scheduled for at least
one surveillance and synchronous interrogation per
scan, and possibly two or more in cases where extended

length messages are being communicated. Multiple
hits are not required at the ground for accurate
azimuth measurements in DABS, because the off-bore-
sight monopulse measurement which is made can be quite
accurate on a single hit. Thus, in some cases, the
SS-CAS aircraft will have only one synchronized reply
per scan to work with in determining target position.

3.2.2   Geometry and Position Measurement Algorithm

        In this section, we explain how the SS-CAS-
equipped aircraft makes use of the information avail-
able in the interrogations and replies to determine
both its own position and that of any nearby target
aircraft. For convenience, the presentation format
used in Section 2 is retained; the initial description
is given in terms of a static situation, and this is
followed by a flow chart presentation of the full
algorithm. The equations for the algorithm are set
forth in tables in the Appendix. For procedures that
do not differ from the ATCRBS case, the reader will
be referred to Section 2.2.

As stated previously, two options for position measurement are presented, each in the format described above. Each is introduced with an explanation of the rationale for its inclusion.

Option I

A desirable feature of the ATCRBS algorithm presented in Section 2 is that differential arrival times can be computed without having to detect the SLS pulse (P_2) of the interrogation to which the target responds. This circumstance holds because ATCRBS interrogation times occur in a periodic fashion easily discernible to the SS-CAS processor. The avionics benefit discussed in Section 2.2.3 is incurred by exploiting this observation.

Due to the irregularity of DABS interrogations, the ATCRBS technique cannot be straightforwardly extended to preserve this feature for the DABS environment. One way to retain the advantage is to include in each synchronized interrogation some surveillance data measured on the previous surveillance call. The DABS aircraft repeats the data in its reply,

3-18

allowing any SS-CAS aircraft which receives the reply
to make use of the data. This will require the addi-
tion of a 112 bit synchronous reply format not found
in the present DABS standard.

The ground-based surveillance system measures
azimuth and range from the target reply, and, as we
will demonstrate, both must be uplinked to accomplish
the stated goal. The overall measurement geometry
for the DABS situation is shown in Figure 3-6; the
notation used coincides with that in the ATCRBS section.
In order to complete the motivation, certain results
which are demonstrated in the sequel are quoted here
without proof.

In the DABS environment, the SS-CAS aircraft
can measure its own position relative to the sensor
(R_1, Ψ_S, h_S) from the DABS/ATCRBS signals in space.
In addition, range to the target (R_3) can be measured
directly. None of these measurements require P_2 pulse
correlation. Figure 3-7 shows what happens if this set
of data is augmented by reception of a target synchronous
reply carrying either range (R_2) or azimuth (Ψ_T), and
of course altitude (h_T), which is in the reply in any
event. If range is included, the situation is as
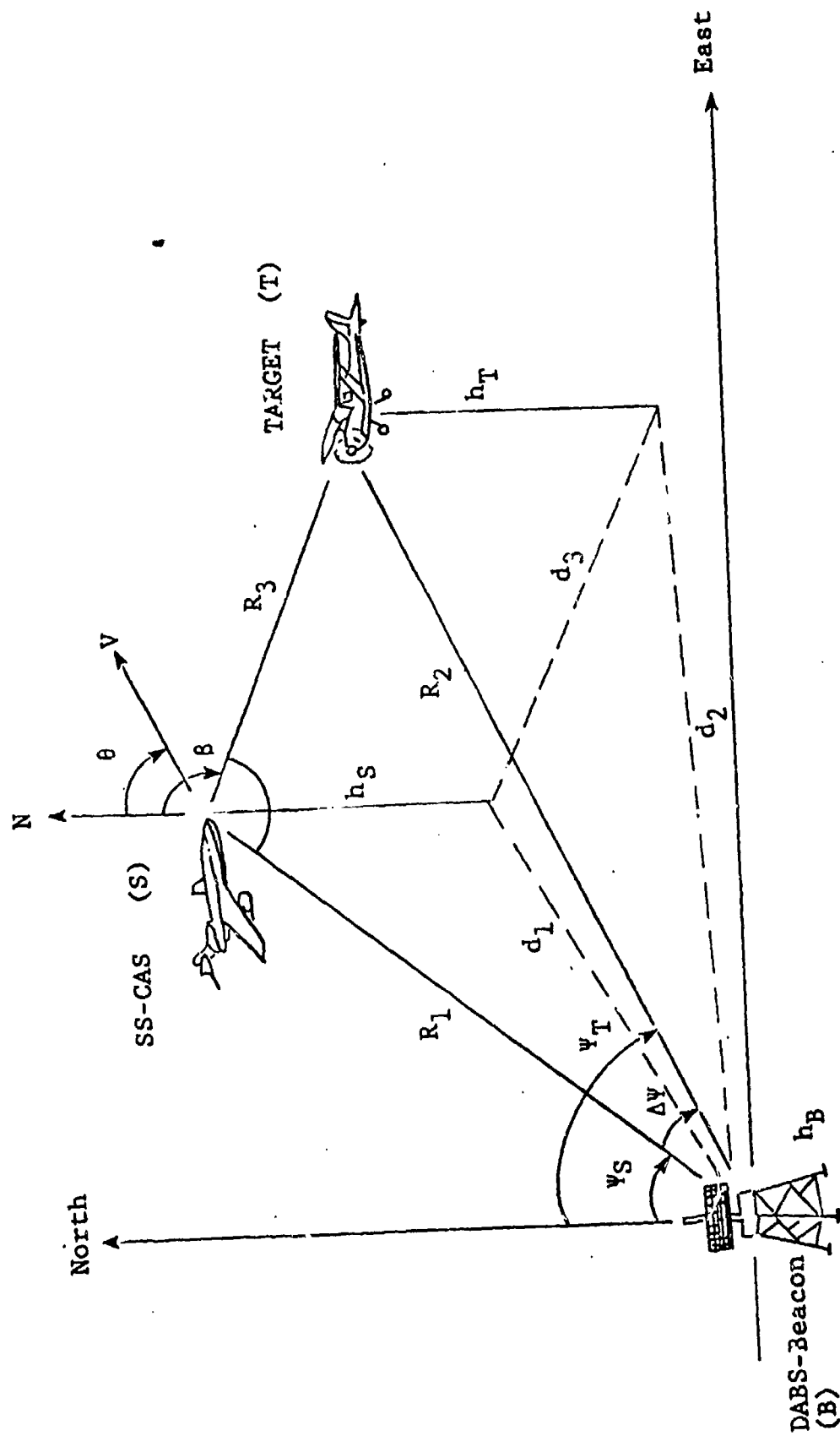shown in (a). Knowledge of R_2 and R_3 constrains the

3-19

Figure 3-6: Single Site Geometry: All-DABS Environment
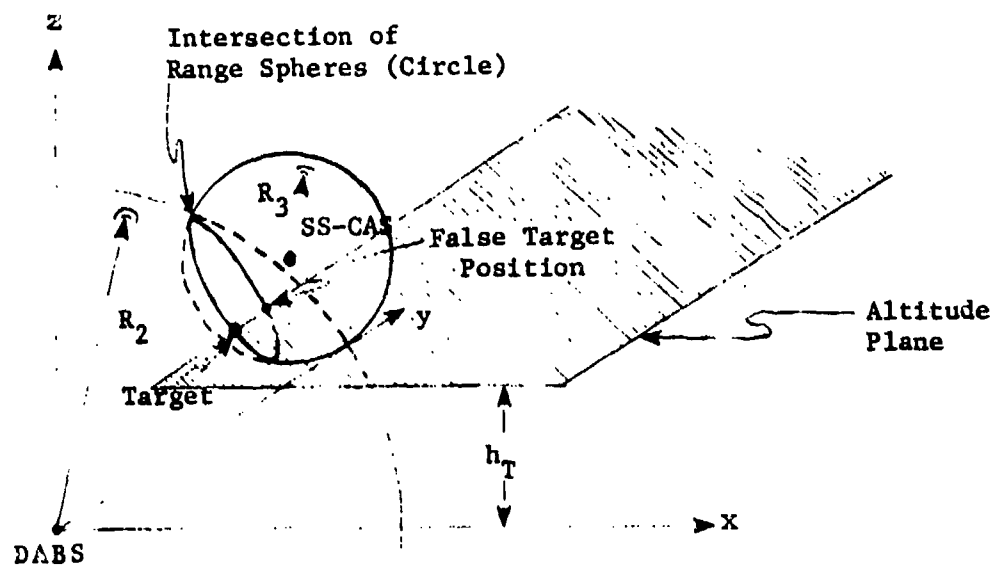
(a) Uplink range (R_2) only
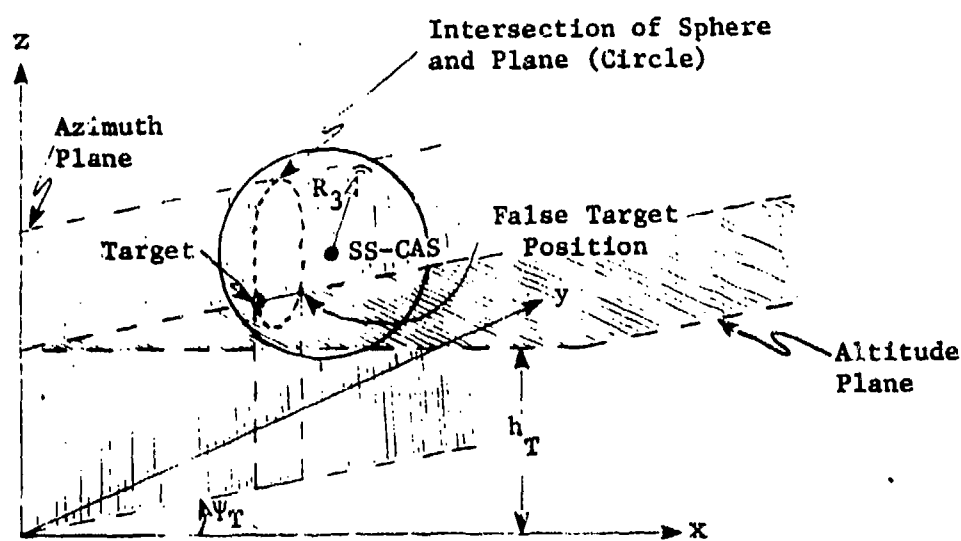
(b) Uplink azimuth (Ψ_T) only

Figure 3-7: DABS Measurement Geometry With One
Target Coordinate Uplinked

target to lie on the intersection of two spheres (which is a circle). The altitude plane cuts this circle in two points, one of which represents a false solution.[*] If the retransmitted coordinate is azimuth, (b) shows that the azimuth plane and the range sphere intersect in a circle, again leaving a spurious solution when the altitude constraint is applied.[*] In either case, the missing coordinate resolves the ambiguity.

The decision to uplink both azimuth and range has some telling consequences. Now a target DABS reply received by SS-CAS contains a full 3D position report on the target; the report is fresh, since it comprises azimuth and range measured one DABS block ago (2.5 ms) and altitude measured at reply time. More-over, SS-CAS is being interrogated by the same DABS beacon and is receiving reports of its own azimuth and range from the site via the data link. Thus, SS-CAS need not even measure its own position. SS-CAS deter-mines both its own and the target position relative to

---

[*] The extraneous solution merges with the true one in the event that the circle is tangent to the alti-tude plane.

the site by decoding the interrogation of SS-CAS, the target reply, and the onboard altimeter. As long as only relative and not absolute position is desired, the GB-DABS link is not required. No accurate time of arrival measurements or solutions of 3D geometry are required. The two position measurements are readily converted to a common time base by measuring time of arrival of target reply with respect to arrival of SS-CAS interrogation and updating with rate information out of the tracker. High quality of position data will be maintained since: (1) the monopulse-corrected azimuth measurement made at the ground is more accurate than any of the airborne techniques, and (2) range accuracy should be comparable to air-derived range, the trade-off at the ground being the gain of the directional DABS antenna versus the long range at which some of the measurements must be taken.

For every reading of target ID, the parity overlay can be omitted in the synchronous reply.

In brief, the Option I solution can be characterized as follows:

3-23

- Minimal number of measurements
- Minimal computational requirements
- High accuracy position determination
- Heavy reliance on ground-based sur-
  veillance and DABS data link

The static measurements are summarized below.
For the full algorithm, including dynamics correction,
see Table A-2. A flow chart presentation of the
algorithm is given in Figure 3-8.

a) R_1 (Range - SS-CAS to Beacon)

   Decoded from synchronous interrogation

b) Ψ_S (SS-CAS Azimuth)

   Decoded from synchronous interrogation

c) h_S (SS-CAS Altitude)

   Decoded from encoding altimeter

d) R_2 (Range - Target to Beacon)

   Decoded from target synchronous reply

e) Ψ_T (Target Azimuth)

   Decoded from target synchronous reply

f) h_T (Target Altitude)

   Decoded from target synchronous reply

3-24
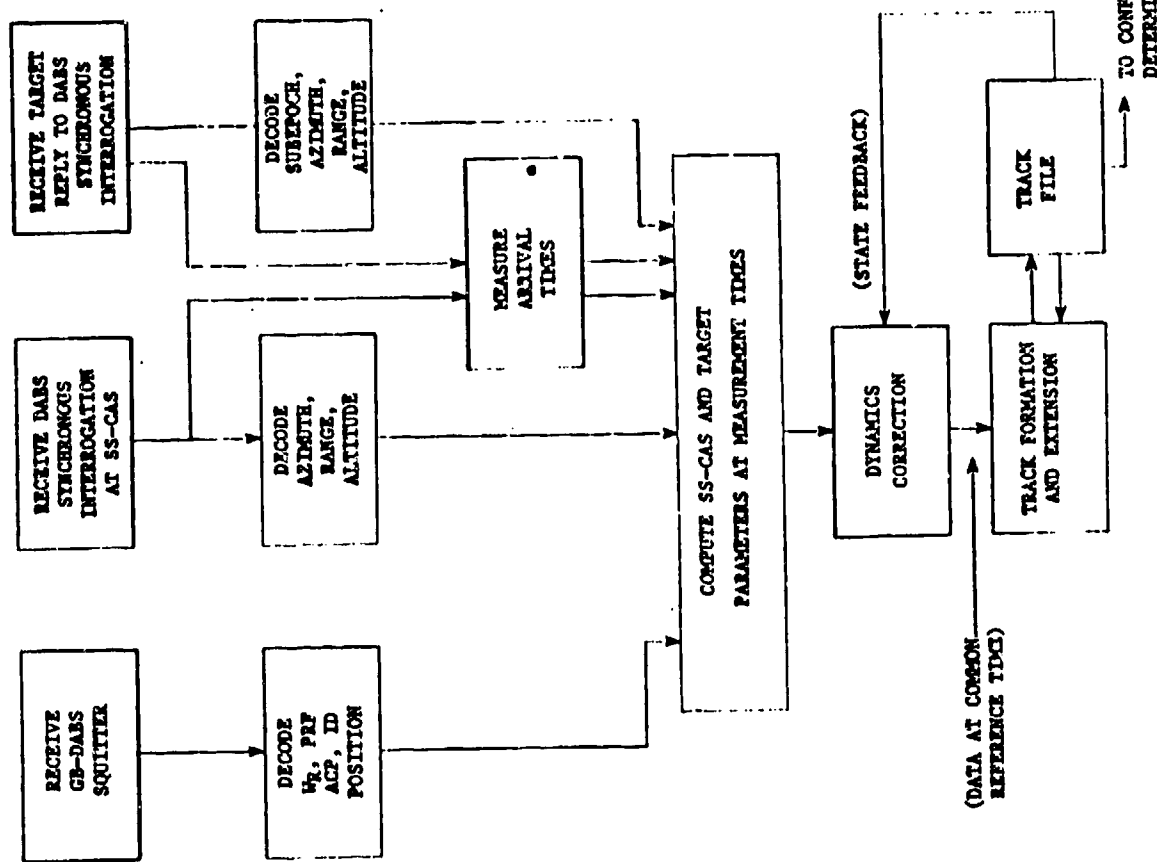
Figure 3-8. Flow Chart of Position Determination Algorithm, DABS Environment (Option I)

Option II

Under Option II, a failure of either the ground data processing or the DABS data link incapacitates SS-CAS. Nevertheless, it is possible to define an option for the DABS era which is independent of the results of the ground surveillance; such a configuration is presented here as Option II. As discussed previously, if it is required to know with precision the time of transmission of a DABS interrogation, it must be measured. Thus, P_2 pulse correlation is an integral part of Option II.

In this option (reference Figure 3-6), SS-CAS aircraft measures its azimuth by centermarking on the ATCRBS interrogations. Range (R_1) can be determined either by interrogating GB-DABS (as in the ATCRBS case) or by measuring time between a DABS T_o and receipt of the following ATCRBS interrogation. Altitude is read from the onboard altimeter.

Range to target (R_3) is computed directly from arrival time of a DABS target synchronous reply. Differential time of arrival (using P_2 pulse correla-

3-26

tion) indirectly gives the target's range to the site (R_2). By projecting the three-range triangle onto the ground, differential azimuth can be computed. This projection uses the site (read from the altimeter) and target (decoded from reply) altitudes.

Thus, the main attributes of Option II are:

- Moderate number of measurements

- Moderate computational requirements

- Accuracy comparable to ATCRBS case

- Greater independence from ground surveillance data and DABS data link

- Requirement for a more sensitive receiver than in Option I.

A more detailed explanation of the procedure follows in the next few paragraphs. The algorithm description is completed in Table A-3 (dynamic measurement equations) and Figure 3-9 (flow chart).
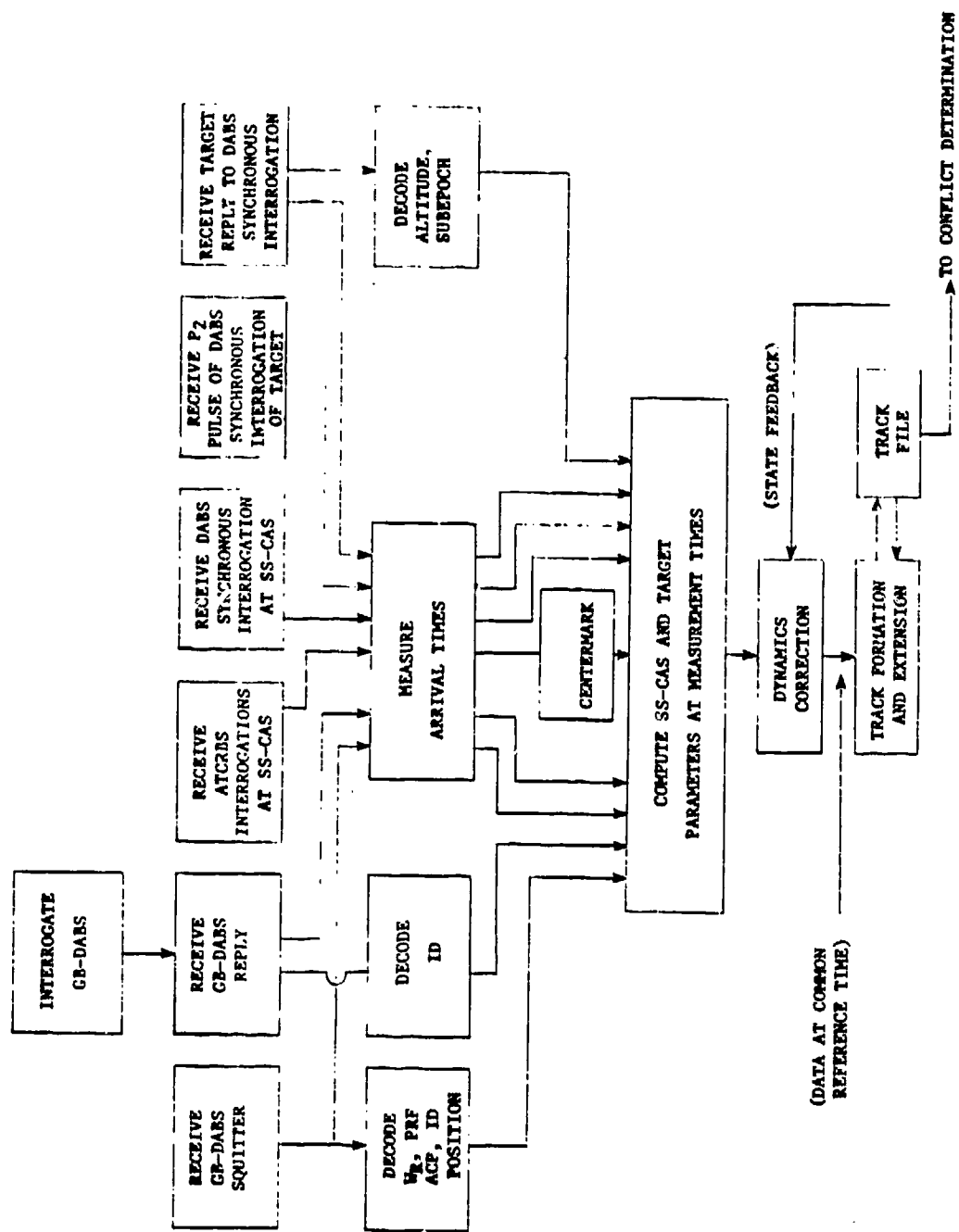
Figure 3-9: Flow Chart of Position Determination Algorithm, DABS Environment (Option II)

3-28

a) R_1 (Range – SS-CAS to Beacon)

Two methods are available. The first
is by two-way ranging on the GB-DABS
(See Section 2.2). The second method
exploits the synchronism between DABS
and ATCRBS interrogations. Looking
back to Figure 3-1 and 3-3, we see that
the T_0 of a DABS synchronous block is
in the exact center of the block and thus
occurs $T/4$ seconds prior to the fol-
lowing ATCRBS interrogation transmission
(T = ATCRBS PRP). SS-CAS determines
the site T_0 and uses it to one-way range
on the succeeding ATCRBS interrogation.

The receiver decodes:

- PRP from the squitter

- SS-CAS subepoch number from
  most recent DABS synchronous
  interrogation (k_S)

The receiver measures:

- Time of arrival of the most
  recent synchronous interrogation
  ($t_{1S)}$

- Time of arrival of the succeed-
  ing ATCRBS interrogation (t_1)

Then,

3-29

$$T_o = t_{1S} - k_S\Delta \quad ; \quad \Delta = \text{subepoch duration}$$

$$R_1 = c(t_1 - T_o - T/4)$$

The latter method of ranging results in a minimal amount of active interrogation by the SS-CAS aircraft. On the other hand, we shall see that ranging on the ATCRBS arrival times does not entirely supplant the DME-type ranging function. In the single site case, the two methods may be used individually, or as partially redundant checks. In the multisite situation, both are needed, as independent information can be gleaned from each (see Section 3.3).

b) Ψ_S (SS-CAS Azimuth)

(As in Section 2.2)

c) h_S (SS-CAS Altitude)

(As in Section 2.2)

d) R_3 (Range – SS-CAS to Target)

The receiver measures:

- The time of arrival at SS-CAS of target reply to a synchronous interrogation (t_{3S})

The receiver decodes:

- Target subepoch number from
the target reply to a synchron-
ous interrogation (k_T)

Knowing that the target reply time
was $T_o + k_T\Delta$,

$$R_3 = c(t_{3S} - T_o - k_T\Delta)$$

e) ΔR (Differential Range $= R_2 + R_3 - R_1$)

ΔR is found by measuring the ΔTOA
between arrivals at SS-CAS of a beacon
interrogation of the target and the
target reply. Since DABS interrogation
transmission times are not precisely
predictable due to their dynamic de-
pendence on aircraft position, the
interrogation must be detected by P_2
pulse correlation.

The receiver measures:

- Time of arrival of the P_2 pulse
of the beacon interrogation
of target (t_{TP2})

Then,

$$TOA = t_{3S} - t_{TP2} - k_T$$

$$R = c*\Delta TOA$$

Since R_1 and R_3 are already known,

$$R_2 = \Delta R + R_1 - R_3$$

3-31

f) h_T (Target Altitude)

Target altitude is decoded from the
surveillance field of the target's
reply to a synchronous interrogation.

g) h_B (Beacon Altitude)

(As in Section 2.2)

h) Ψ_T (Target Azimuth)

Differential azimuth ($\Delta\Psi$) is calculated
from the ground projections of the
ranges R_1, R_2, and R_3. Those projec-
tions d_1, d_2, and d_3, are calculated
as in Section 2.2.

Then,

$$\cos \Delta\Psi = \frac{d_1^2 + d_2^2 - d_3^2}{2d_1 d_2}$$

This equation determines $\Delta\Psi$ except
for algebraic sign. Sign ambiguity
can always be resolved if SS–CAS and
target are interrogated in separate
synchronous DABS blocks by testing
whether the SS–CAS or the target P_2
pulse arrives first:

$\longrightarrow \Delta\Psi < 0$

$t_{SP2} \gtrless t_{TP2}$

$\longrightarrow \Delta\Psi > 0$

3-32

where t_{SP2} denotes arrival time of the
P_2 pulse of the beacon interrogation
of SS-CAS. Positive $\Delta\Psi$ is taken in
the sense of the beacon rotation.

If the two aircraft are interrogated
in the same block, the question may not
be resolvable, since range takes priority
over azimuth in the synchronous scheduler.
However, resolution is hardly necessary
in the latter case, since $|\Delta\Psi|$ must be
small in order that the two are within
the same block (the beacon rotates only
about 0.05° during the maximum time
span of one synchronous interrogation
cycle, and the interrogated aircraft
are usually no more than $\pm0.2^{\circ}$ from the
boresight in order to accommodate the
ground-based monopulse processor). In
such cases the sign may as well be
determined by the test given previously.

Then,

$$\Psi_S = \Psi_T + \Delta\Psi$$

i) β (Target Relative Bearing)

(As in Section 2.1)

These equations complete the static measurement des-
cription.

3-33

The dynamic measurements differ in that some
of the measurements which are based on the ATCRBS
signals involve multiple hit processing (centermarking),
whereas in other ATCRBS (and all DABS) cases, single
hits are processed. As in the all-ATCRBS measurement
algorithm, dynamic corrections for aircraft motion
and time lapse between measurements are required. The
equations for the entire procedure are summarized in
Table A-3.

3.2.3   Data Link Considerations

The SS-CAS/GB-DABS data link, as described
in Section 2.2.2 and Figures 2-5 and 2-6 is fully
compatible with the requirements of the all-DABS
environment. The only unfinished business from that
section is the matter of the representation of the
antenna position (ACP count). Because the allocation
of channel time at a DABS/ATCRBS site is more stringent
than at an ATCRBS-only site, there are tighter con-
straints upon the time at which the quadrant squitters
can occur. In this section we show that the ACP count
format in the squitter is adequate to meet the demands.

Recall that the constraint on squitter time is that the 1090 MHz squitter cannot be transmitted while the beacon receiver is open to receive replies at that same frequency. Referring back to the channel schedule shown in Figure 3-1, we see that the worst case delay in squitter time would result when the North (or other direction) passage time coincides with the center (i.e., T_o) of a DABS synchronous block. The latter half of that block is a DABS listening interval, and the entire ATCRBS interval which follows is a listening interval, since an ATCRBS aircraft could be arbitrarily close to the site. The delay is $3T/4$ (1875 μs at a PRP=400 pulse/second site), which corresponds to less than 2 ACP counts. Then the 4 bit format presented in Section 2.2.2 suffices for this case as well.

3.2.4   Avionics Considerations

The avionics package for the DABS environment is basically that described in Section 2.2.3. There are variations according to the option which is implemented. The Option I package is essentially

identical to the ATCRBS package. Option II necessitates a more sensitive receiver for detection of the SLS pulse. No new antenna requirements are foreseen. The computational requirements for Option I are far simpler than in the ATCRBS case; for Option II they are equivalent.

3.2.5   Tracker Considerations

It is not necessary to dwell in depth on the DABS-environment tracker, since it is not the pacing item in the concept, as it appears to be in the ATCRBS case. To reemphasize, in the DABS/ATCRBS single site case, all the signals (both interrogations and replies) with which the SS-CAS processor must work arrive garble-free at the SS-CAS aircraft. Features such as the azimuth-aided degarbling or "true zero" processing described earlier need not be incorporated. Since each DABS reception contains the address code of the transmitter or intended recipient, track association and extension become almost trivial, and formation is simplified inasmuch as correct ID can be obtained from one or two receptions.

Thus, the tracker in the DABS case is much simpler than the ATCRBS tracker.

3.3   SS-CAS in a High Density, Multiple DABS
        Site Environment

When the SS-CAS aircraft is in a region of fairly dense air traffic, there will be many occasions upon which SS-CAS and/or the target aircraft will have multiple coverage from DABS/ATCRBS sites. Although this situation can pose a synchronous garble problem not found in the single-site case, it can also present some opportunities for improved or extended coverage. Two examples illustrate some possibilities.

Example 1:

Consider the situation depicted in Figure 3-10 in which SS-CAS and the target lie in separate DABS sensor coverage zones. Although both have DABS coverage, they are interrogated by different ground sites. SS-CAS (under DABS B_1 coverage) can detect target replies (under DABS B_2 coverage), but cannot use them

3-37

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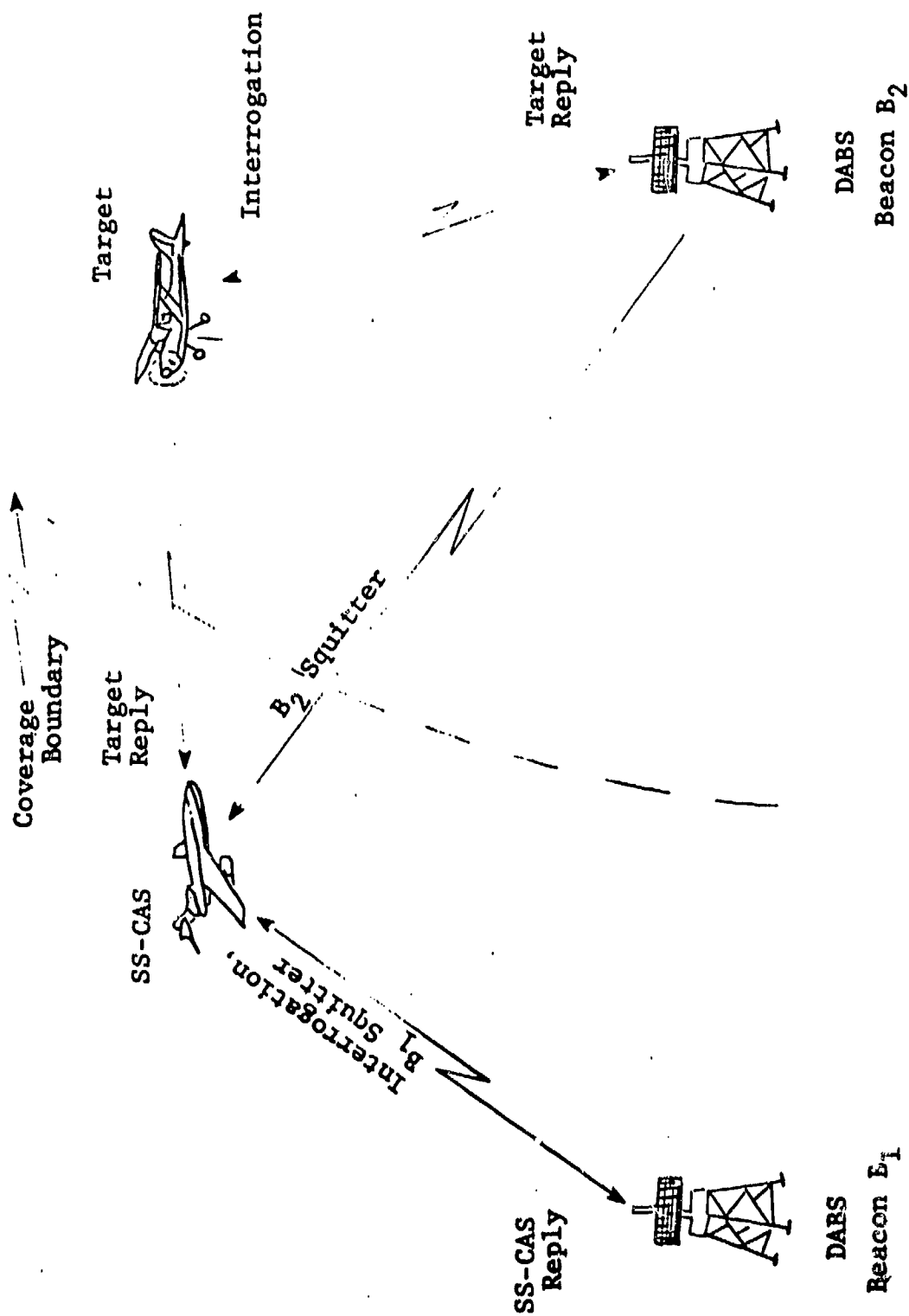
Figure 3-10: SS-CAS Tracking Aircraft Interrogated by Another Site

to measure target position because it does not know the
DABS B_2 time-base. Since the target could be close
enough to be a threat, SS-CAS requires a means to
utilize the target replies. A solution to that problem
is given in this section.

Example 2:

    The positions of SS-CAS and target relative
to the interrogating site are poor ones for target
position measurement. In the situation shown in
Figure 3-11, the GDOP (geometric dilution of precision)
for Option II SS-CAS is large because of the almost
tangential contact of the range sphere and the ΔTOA
ellipsoid. Better geometry would result if the al-
ternative site were used. Multi-site coverage of the
target aircraft can be exploited to provide the pre-
ferred measurement.

3.3.1   Tracking Aircraft Interrogated by Another Site

    We return to the problem stated in Example 1
and Figure 3-10. SS-CAS receives interrogations from

3-39
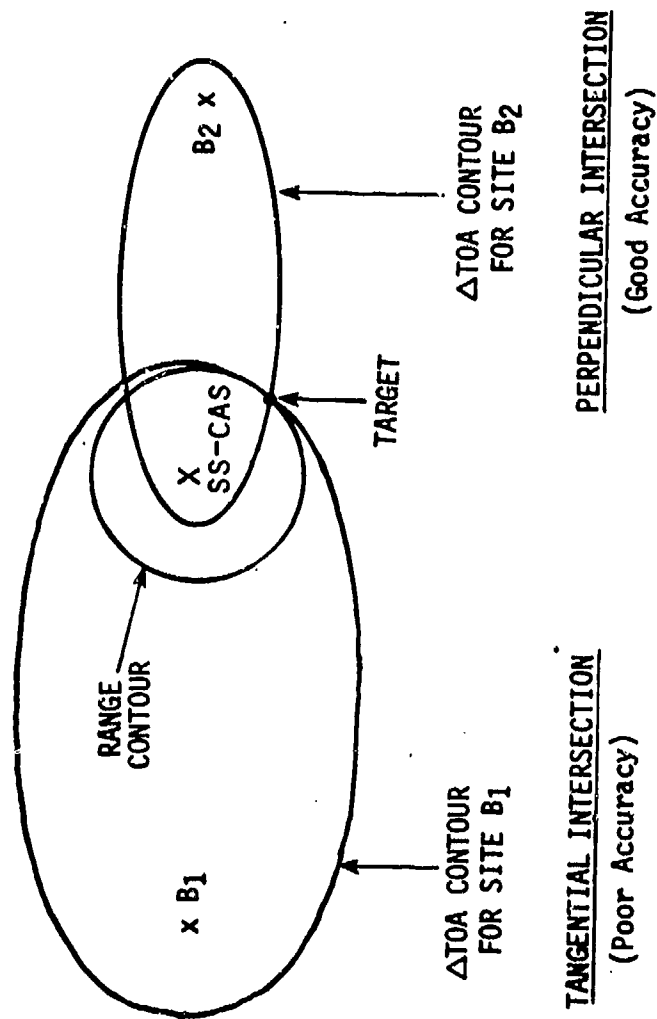
Figure 3-11: Site Selection for Improved DABS-Target Tracking Accuracy

sensor B_1 and target replies in response to interrogations by sensor B_2, but cannot use the latter for position measurement due to lack of timing information. In order to get the information required, SS-CAS must be able to communicate with the transponder at the ground site which is interrogating the target. The vehicle for this is the SS-CAS/GB-DABS link which has been described earlier (see Section 2.2.2).

Recall that the parameters of the data link were determined so that the communication reliability on a per-information bit basis would be equal to that on an ATCRBS link operating at the same range. Therefore, this link will also be adequate to communicate with an adjacent DABS sensor located across a coverage boundary. The argument goes as follows (refer to Figure 3-10): an adjacent site is only of interest to SS-CAS if (i) it is interrogating a nearby DABS aircraft, and (ii) if that aircraft is near enough SS-CAS to be a potential threat. The range from SS-CAS to the adjacent DABS sensor is certainly less than the sum of the site-to-target and target-to-SS-CAS ranges. Because of proposition (ii) above, the latter range is usually small compared to the former,

which means that the SS-CAS-to-DABS range cannot
significantly exceed the stipulated maximum range.
Indeed, DABS coverage boundaries will ordinarily not
be at maximum range from the site, indicating that
SS-CAS will almost always be interrogating GB-DABS
within nominal range. Since the link has been configured
such that the uplink and downlink reliabilities are
equal, these considerations apply to the reply and
squitter functions as well.

SS-CAS detects a neighboring site by receipt
of its squitter. This will give SS-CAS the position
and ID of the site, and its PRF as well. This data is
sufficient for SS-CAS to track aircraft from such
sites, as shown below and with reference to Figure 3-10,
for both Options I and II.

Option I

Upon receipt of a target reply, SS-CAS de-
codes target position relative to B_2. To enable
SS-CAS to know which site is tracking a given target,
each DABS sensor includes its 4-bit ID in the message
portion of every synchronous interrogation. The ID

is repeated in all synchronous replies. The same holds
for Option II. From the B_1 and B_2 squitters, SS-CAS
knows the two site positions and can convert target
position into either an absolute frame or one refer-
enced to site B_1.

Option II

Upon receipt of a target reply to B_2, SS-CAS
knows the time of reply relative to the T_o of B_2; it
does not yet know T_o, however. It cannot be obtained
directly, as B_2 is not interrogating SS-CAS. Instead,
T_o is inferred by first measuring the SS-CAS-to-B_2
range, which can be computed directly from the position
data in the B_1 and B_2 squitter receptions. It can also
be measured directly by interrogating the GB-DABS at
B_2. Once range is known, SS-CAS can work backwards
from the receipt of a B_2 ATCRBS interrogation to learn
when that interrogation was transmitted. T_o occurs
a fixed amount ahead of that time; the exact amount
depends only on the PRF of the site, which SS-CAS
also knows from the B_2 squitter. Knowing T_o, direct
target-to-SS-CAS range and all of the other target
parameters can be computed as the target is tracked.

As in all other SS-CAS measurements, dynamic corrections must be made. These can be done exactly as in the single site case.

Having established the ability to utilize sites other than the one(s) interrogating SS-CAS, we can turn our attention to the issue raised by Example 2, which is selection of sites for improved accuracy. Any target being interrogated by more than one DABS site provides options in site selection. Typically, aircraft near DABS coverage boundaries are capable of multiple interrogation. The example showed that the geometry, taken from a GDOP point of view, tends to be more favorable if the target lies between SS-CAS and the interrogating site. Thus, the tendency will be to select a site which lies at roughly the same bearing (relative to SS-CAS) as the target to be tracked. We emphasize that the issue here is strictly accuracy and not garble-freedom, as was the major site selection issue for ATCRBS.

Garble in the multi-site situation must nevertheless be addressed. Synchronous garble is not likely to be an issue, since adjacent sites will have

differing PRF's and a desired reply from a B_1 inter-
rogation is unlikely to be garbled more than once by
a fruit return elicited by B_2. Self-site garble will
not occur; that is, if SS-CAS is tracking targets T_1
and T_2 from B_2, the synchronous replies from T_1 and
T_2 will not garble at SS-CAS (or anywhere else) be-
cause of the interrogation strategy.

There remains the problem of ATCRBS fruit;
in part, this is more properly treated as a transi-
tion issue and is discussed as such in Section 4;
however, inasmuch as there is a low level ATCRBS fruit
problem in any environment in which ATCRBS is present,
it must be accounted for in the concept formation
insofar as the tracker is concerned.

The DABS signals which could be garbled at
SS-CAS are transponder replies (target or GB-DABS),
which are PPM 1 MHz data rate signals. The garbling
ATCRBS replies are PAM signals of duration 0.45 µs
and rate 1 MHz. Thus, the "ON" pulses of each type
are quite similar. Measures similar to those des-
cribed for the ATCRBS tracker can be employed for garble
detection and, in some instances, correction.

A DABS PPM reply contains exactly one "ON" pulse per bit period. A garble distortion which adds a pulse in the "OFF" slot or, more rarely, cancels the "ON" pulse, leaving a blank bit, is readily detectable, but not necessarily correctible. Unlike the all-ATCRBS situation, successive reply garbles will be totally independent, since they are single hits spaced in time by a full scan of the antenna. In that case successive returns can be correlated for error correction of fixed data (e.g., aircraft ID). In performing the correlation one can exploit the principle that garble rarely destroys the "ON" pulses, but will quite likely fill in the "OFF" slots. No azimuthal end effects such as are found in the ATCRBS target tracker are present here, because end effects require reply runs, which do not exist for DABS.

4.   SS-CAS IN THE TRANSITION ENVIRONMENT

The transition environment is that which exists during the process of evolutionary upgrading of the ground-based ATC surveillance system from ATCRBS to DABS. In transition, some DABS/ATCRBS sensors have become operational, and not all ATCRBS-only beacons have been decomissioned or converted. Each ground site has a GB-DABS transponder. The airborne transponder population is a mix of ATCRBS Mode C and DABS/ATCRBS units.

Since each DABS ground interrogation interleaves ATCRBS and DABS interrogations, replies (to a single interrogation) received by an SS-CAS aircraft will be either all ATCRBS or all DABS. The SS-CAS aircraft can sequentially process and track ATCRBS transponder-equipped aircraft and DABS transponder-equipped aircraft. Thus, the operation of SS-CAS in a mixed airspace environment is simply an interleaving of the techniques used for ATCRBS target tracking, as described in Section 2, and the techniques used for DABS target tracking, as described in Section 3.

4.1 Compatibility

With respect to the ATCRBS → DABS transition itself, the recommendation made by the Air Traffic Control Advisory Committee in 1969 (Reference 10) that the replacement of ATCRBS by DABS be: (i) an evolutionary process, and (ii) both upward and dpwnward compatible, is being followed. The DABS design reflects this in that a DABS transponder can issue ATCRBS replies to ATCRBS interrogations if desired, and a DABS sensor both transmits ATCRBS as well as DABS interrogations and processes ATCRBS replies from any transponder.

The SS-CAS design is fully compatible with this surveillance transition. As evidenced in the two preceding sections of this report, SS-CAS has been designed to offer full CAS service in both an all-ATCRBS and all-DABS environment.

4.2 Synchronous Garble and Fruit

The role of ATCRBS synchronous garble (for ATCRBS equipped targets) relative to SS-CAS functions

has been recognized and dealt with in the tracker design. Although synchronous garble can be abated considerably by judicious tracking and signal processing, there is of course a limit point at which the system would break down. This limit point, however, may not be reached today for the surveillance system, even in the highest density traffic/interrogator environments. Furthermore, the transitional trend is towards a decrease in synchronous garble as ATCRBS transponders are replaced by DABS transponders. As we have seen, synchronous garble in DABS is not an issue.

Asynchronous garble ("fruit") in the ATCRBS environment is dealt with effectively by the ATCRBS tracker. In DABS tracking, ATCRBS fruit is partially mitigated by advanced signal processing. Fortunately, fruit levels high enough to cause serious ATCRBS degradation have rarely been observed, and, of course, these levels will decay with time.

4.3   Distribution of DABS and ATCRBS Interrogations

In the first implementation of SS-CAS, the
environment would be essentially all-ATCRBS, and the
anticipated performance would be as described earlier.
As DABS becomes increasingly prevalent, there will be
lesser amounts of ATCRBS garble and, correspondingly,
a decreasing need to process long reply runs on ATCRBS
targets. Thus, there can be a shift in interrogator
strategy towards allowing more DABS synchronous blocks
and fewer ATCRBS blocks. ATCRBS cannot, and would not,
be phased out entirely, but azimuth and ΔTOA accuracy
can be maintained for ATCRBS targets in decreased
garble with fewer (but clear) hits. The increased
DABS time can be used for capacity increase (to help
compensate for the longer synchronous reply) or multiple
synchronous calls for improved CAS accuracy.

4.4   Pop-up Targets

The pop-up target was an issue in the all-
ATCRBS environment because targets out of ground cover-
age are not passively detectable. The clear volume

for relatively garble-free active interrogation is not as large as one might like. In DABS, however, out-of-coverage targets are passively detectable and can be tracked actively until they enter coverage or are no longer of interest. Thus, during the transition, the pop-up target problem should lessen for SS-CAS, and furthermore, the amount of active interrogation required to track out-of-coverage targets should decrease.

4.5   Dependence on Ground Surveillance

The integrity of service of a beacon-based CAS is tied to the integrity of the ground transmissions. There is a question of whether the dependence on the ground system should be permitted to go beyond that. This issue was raised in the presentation of two options for tracking DABS targets. Briefly, Option I utilizes retransmission of ground-derived azimuth and range and results in a very uncomplicated data processing situation at the SS-CAS aircraft. Option II has no such retransmission, but as a result both the processing complexity and the avionics requirements are increased.

Option I can live in a totally DABS world
in which ATCRBS is no longer transmitted anywhere.
Of itself, this is no particular advantage since
ATCRBS is protected by international treaty for some
time to come and will certainly perpetuate beyond the
expiration date. Some protection against short term
outages of the ATCRBS function at a DABS/ATCRBS site
is afforded, however. Of course, processing failures
at the ground interrupt Option I SS-CAS service.

Option II is independent of such processing
failures. The increased airborne processing require-
ment (relative to Option I) is not much an issue; the
complexity is only about equal to that of the ATCRBS
processor/tracker. A more pertinent question is the
heavier initial investment required to obtain a receiver
with sensitivity enough to detect the SLS pulses.
The Option II avionics package is certainly the more
powerful of the two and, once acquired, will provide
full service for the lifetime of DABS. The same cannot
quite be said for Option I.

Both options have the required evolutionary
compatibility; they merely lead to slightly different
endpoints.

APPENDIX

This Appendix contains the three tables which give the full, dynamically-corrected three-dimensional position determination equations for the all-ATCRBS environment (Table A-1) and the all-DABS environment, Option I (Table A-2) and Option II (Table A-3).

Table A-1: Position Determination Procedure, ATCRBS Environment

Measure: τ_1, δt_1, t_{oS}, t_{oT}, $\{t_1(i)\}$, $\{t_{2+3}(i)\}$

where $\quad$ $i = 1, 2, \ldots N^*$: N = maximum number of sweeps/scan

τ_1 = Time of most recent interrogation of GB-DABS

δt_1 = Round trip time of SS-CAS interrogation of GB-DABS

t_{oS} = Time of arrival of most recent GB-DABS squitter prior to ATCRBS interrogation of SS-CAS

t_{oT} = Time of arrival of most recent GB-DABS squitter prior to ATCRBS interrogation of target

$t_1(i)$ = Time of arrival of ith mainbeam interrogation of SS-CAS

$t_{2+3}(i)$ = Time of arrival at KCAS of ith target reply to ATCRBS interrogation

Data Received:

Decoded from GB-DABS squitter:

W_R = Rotation rate of ATCRBS beacon

PRF = Interrogation rate of ATCRBS beacon

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* Because ATCRBS round reliability is <100%, measurements may not be available for some of the indicated values of the index i.

Table A-1: Position Determination Procedure, ATCRBS Environment (Continued)

ACP_S = Azimuth change pulse count at time of most recent GB-DABS squitter prior to ATCRBS interrogation of SS-CAS

ACP_T = Azimuth change pulse count at time of most recent GB-DABS squitter prior to ATCRBS interrogation of target

(e) h_B = Altitude of ATCRBS beacon *

Decoded from target aircraft replies:

$h_T(i)$ = Altitude of target in i^{th} Mode C reply

Decoded from SS-CAS aircraft altitude encoder:

$h_S(i)$ = Altitude of SS-CAS aircraft at i^{th} Mode C reply time

Compute:

$\hat{t}_1$ = Centermark-estimated time of arrival of (hypothetical) beacon interrogation of SS-CAS when SS-CAS lies at center of main beam; computed from

$$\{t_1(i) : i = 1, 2, \ldots N\}$$

$\dot{R}_1$ = Range rate of SS-CAS aircraft from ATCRBS beacon (provided by tracker)

(a) R_1 = Range of SS-CAS aircraft from ATCRBS beacon at time $\hat{t}_1$

$$= c\delta t_1/2 + \dot{R}_1(\hat{t}_1 - \tau_1)$$

* Letter designators such as (e) before equations designate the corresponding equation in the text (Section 2.2.1)

A-3

Table A-1: Position Determination Procedure, ATCRBS Environment (Continued)

ψ_{BS} = Squittered main beam angle received at t_{oS}

$\quad = 0.0879° \star ACP_K$

$\dot{\psi}_S$ = $d\psi_S/dt$ (provided by tracker)

(b) ψ_S = SS-CAS azimuth at time $\hat{t}_1$

$\quad = \psi_{BS} + \dot{\psi}_R(\hat{t}_1 - t_{oS})$

$\hat{t}_{2+3}$ = Centermark-estimated time of arrival of (hypothetical) target reply at SS-CAS to an interrogation received by target when target lies at center of main beam; computed from

$$\{t_{2+3}(i) : 1, 2 \ldots N\}$$

ψ_{BT} = Squittered main beam angle received at t_{oT}

$\quad = 0.0879° \star ACP_T$

$\dot{\psi}_T$ = $d\psi_T/dt$ (provided by tracker)

(c) ψ_T = Target azimuth at time $\hat{t}_1$

$\quad = \begin{cases} \psi_{BT} + \dot{\psi}_R (\hat{t}_{2+3} - t_{oT}) - \dot{\psi}_T(\hat{t}_{2+3} - \hat{t}_1) \\ \psi_S + (\dot{\psi}_R - \dot{\psi}_T) (\hat{t}_{2+3} - \hat{t}_1) \end{cases}$

$\Delta\psi$ = $\psi_T - \psi_S$

A-4

Table A-1: Position Determination Procedure, ATCRBS Environment (Continued)

$$N_{12}(i) + \epsilon_{12}(i) = [t_{2+3}(i) - t_1(i)] * PRF$$

where

$N_{12}(i)$ = nearest integer value ($\pm$) , and $0 < \epsilon_{12}(i) << 0.5$

$\Delta TOA(i) = \epsilon_{12}(i)/PRF$

$\widehat{\Delta TOA}$ = Centermark-estimated differential time of arrival between arrival of target reply at SS-CAS and SS-CAS reply time computed as though both aircraft are interrogated on same sweep

$\Delta R = c*\widehat{\Delta TOA}$

R_2 = Range beacon to target at time $\hat{t}_1$

$$= \frac{\Delta R(\Delta R + 2R_1)}{2[\Delta R + R_1(1 - \cos\Delta\Psi)]}$$

(d) R_3 = Range SS-CAS to target at time $\hat{t}_1$

$= \Delta R + R_1 - R_2$

$\hat{h}_T$ = Altitude of target at time $\hat{t}_{2+3}$
computed from $\{h_T(i); i = 1, 2, \ldots N\}$

A-5

Table A-1: Position Determination Procedure, ATCRBS Environment (Continued)

$\dot{h}_T$ = Target altitude rate (provided by the tracker)

(f) h_T = Altitude of target at time $\hat{t}_1$:

$= \hat{h}_T + \dot{h}_T(\hat{t}_{2+3} - \hat{t}_1)$

(g) h_S = Altitude of SS-CAS at time $\hat{t}_1$: computed from $\{h_S(i); i = 1, 2, \ldots N\}$

$\Delta h = h_S - h_T$

d_1 = Ground range -- beacon to SS-CAS at time $\hat{t}_1$

$= \left[R_1^2 - (h_S - h_B)^2\right]^{\frac{1}{2}}$

d_2 = Ground range -- beacon to target at time $\hat{t}_1$

$= \left[R_2^2 - (h_3 - h_B)^2\right]^{\frac{1}{2}}$

N_S = North coordinate of SS-CAS relative to beacon

$= d_1 \cos \Psi_S$

E_S = East coordinate of SS-CAS relative to beacon

$= d_1 \sin \Psi_S$

A-6

Table A-1: Position Determination Procedure, ATCRES Environment (Continued)

N_T = North coordinate of target relative to beacon

$= d_2 \cos \psi_T$

E_T = East coordinate of target relative to beacon

$= d_2 \sin \psi_T$

σ_N = sgn $(N_T - N_S)$

σ_E = sgn $(E_T - E_S)$

(h) β = Target bearing relative to SS-CAS at time $\hat{t}_1$

$= \tan^{-1} \left[\dfrac{E_T - E_S}{N_T - N_S} \right]$: quadrant assigned according to

		σ_E	
		+	−
σ_N	+	I	II
	−	IV	III

A-7

Table A-2: Position Determination Procedure, DABS Environment (Option I)

Measure: t_{1S}, t_{3S}

where

t_{1S} = Time of arrival at SS-CAS of DABS synchronous interrogation

t_{3S} = Time of arrival at SS-CAS of target reply to DABS synchronous interrogation

Data Received:

Decoded from GB-DABS squitter:

h_B = Altitude of DABS/ATCRBS beacon

Decoded from synchronous interrogation of SS-CAS:

(a)* R_1 = Range of SS-CAS from DABS/ATCRBS beacon at time t_{1S}

(b) Ψ_S = Azimuth of SS-CAS from DABS/ATCRBS beacon at time t_{1S}

Decoded from SS-CAS aircraft altitude encoder:

(c) h_S = Altitude of SS-CAS aircraft at time t_{1S}

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* Letter designators such as (a) before equations designate the corresponding equation in the text (Section 3.2.3)

A-8

Table A-2: Position Determination Procedure, DABS Environment (Option I)
(Continued)

Decoded from target reply to DABS synchronous interrogation:

$\tilde{R}_2$ = Range of target from DABS/ATCRBS beacon at time t_{3S}

$\tilde{\Psi}_T$ = Azimuth of target from DABS/ATCRBS beacon at time t_{3S}

$\tilde{h}_T$ = Altitude of target aircraft at time t_{3S}

<u>Compute:</u>

(d) $\dot{R}_2$ = Range rate of target aircraft from DABS/ATCRBS beacon
(Provided by tracker)

$R_2 = \tilde{R}_2 + \dot{R}_2(t_{3S} - t_{1S})$

(e) $\dot{\Psi}_T$ = Azimuth rate of target aircraft from DABS/ATCRBS beacon
(Provided by tracker)

$\Psi_T = \tilde{\Psi}_T + \dot{\Psi}_T(t_{3S} - t_{1S})$

(f) $\dot{h}_T$ = Altitude rate of target aircraft
(Provided by tracker)

$h_T = \tilde{h}_T + \dot{h}_T(t_{3S} - t_{1S})$

Table A-3: Position Determination Procedure, DABS Environment (Option II)

Measure: τ_1, δt_1, t_{1S}, t_1, t_{oS}, $\{t_1(i)\}$, t_{3S}, t_{TP2}, t_{SP2}

where $i = 1, 2, \ldots N^*$: N = maximum number of sweeps/scan

τ_1 = Time of most recent interrogation of GB-DABS

δt_1 = Round trip time of SS-CAS interrogation of GB-DABS

t_{1S} = Time of arrival at SS-CAS of most recent DABS synchronous interrogation

t_1 = Time of arrival at SS-CAS of succeeding ATCRBS interrogation

t_{oS} = Time of arrival of most recent GB-DABS squitter prior to DABS/ATCRBS interrogation of SS-CAS

$t_1(i)$ = Time of arrival of ith mainbeam ATCRBS interrogation of SS-CAS

t_{3S} = Time of arrival of target reply to a DABS synchronous interrogation

t_{TP2} = Time of arrival of the P_2 pulse of a DABS synchronous interrogation of target

t_{SP2} = Time of arrival of the P_2 pulse of a DABS synchronous interrogation of SS-CAS

_____

* Because ATCRBS round reliability is <100%, measurements may not be available for some of the indicated values of the index i.

A-10

Table A-3: Position Determination Procedure, DABS Environment (Option II)
(Continued)

Data Received:

Decoded from GB-DABS squitter:

W_R = Rotation rate of ATCRBS beacon

PRF = Interrogation rate of ATCRBS beacon

ACP_S = Azimuth change pulse count at time of most recent GB-DABS squitter prior
to DABS/ATCRBS interrogation of SS-CAS

$(g)^*$ h_B = Altitude of DABS/ATCRBS beacon

Decoded from DABS synchronous interrogation of KCAS:

k_S = SS-CAS subepoch number

Decoded from target reply to DABS synchronous interrogation

k_T = Target subepoch number

h_T = Target altitude at time of synchronous interrogation

_____

* Letter designators such as (g) before equations designate the corresponding equation
in the text (Section 3.2.3)

A-11

Table A-3: Position Determination Procedure, DABS Environment (Option II)
(Continued)

Decoded from SS-CAS aircraft altitude encoder:

$\tilde{h}_S$ = Altitude of SS-CAS aircraft at DABS synchronous interrogation reply time t_{1S}

Compute:

$\hat{t}_1$ = Centermark-estimated time of arrival of (hypothetical) ATCRBS interrogation of SS-CAS when SS-CAS lies at center of main beam; computed from

$$\{ t_1(i) : i = 1, 2, \ldots N \}$$

T_o = Center of DABS synchronous interval

$= t_{1S} - k_S \Delta$

T = Pulse Repetition Period

$= 1/PRF$

$\dot{R}_1$ = Range rate of SS-CAS aircraft from ATCRBS beacon (provided by tracker)

(a) R_1 = Range of SS-CAS aircraft from beacon at time $\hat{t}_1$

$$= \begin{cases} c\delta t_1/2 + \dot{R}_1(\hat{t}_1 - t_1) \text{; GB-DABS two-way ranging} \\ c(t_1 - T_o - T/4) + \dot{R}_1(\hat{t}_1 - t_1) \text{; DABS/ATCRBS one-way ranging} \end{cases}$$

A-12

Table A-3: Position Determination Procedure, DABS Environment (Option II)
(Continued)

ψ_{BS} = Squittered main beam angle received at t_{oS}

$\qquad$ = $0.0879° * ACP_S$

$\dot{\psi}_S$ = $d\psi_S/dt$ (provided by tracker)

(b) ψ_S = SS-CAS azimuth at time $\hat{t}_1$

$\qquad$ = $\psi_{BS} + W_R(\hat{t}_1 - t_{oS})$

$\dot{h}_S$ = Altitude rate of SS-CAS aircraft (provided by tracker)

(c) h_S = Altitude of SS-CAS aircraft at time $\hat{t}_1$

$\qquad$ = $h_S + \dot{h}_S(\hat{t}_1 - t_{1S})$

$\dot{R}_3$ = Range rate -- SS-CAS to target (provided by tracker)

(d) R_3 = Range -- SS-CAS to target at time $\hat{t}_1$

$\qquad$ = $c(t_{3S} - T_o - k_T A) + \dot{R}_3(\hat{t}_1 - t_{3S})$

$\widetilde{TOA}$ = Differential time of arrival at time t_{3S}

$\qquad$ = $t_{3S} - (t_{TP2} + k_T A)$

$\widetilde{\Delta R}$ = Differential range at time t_{3S}

$\qquad$ = $c * \widetilde{\Delta TOA}$

A-13

Table A-3: Position Determination Procedure. DABS Environment (Option II)
(Continued)

$\dot{R}_2$ = Range rate -- target to beacon (provided by tracker)

$\Delta\dot{R}$ = Differential range rate

$\quad = \dot{R}_1 + \dot{R}_2 - \dot{R}_3$

ΔR = Differential range at time $\hat{t}_1$

$\quad = \Delta\bar{R} + \Delta\dot{R}(\hat{t}_1 - t_{3S})$

(e) R_2 = Range -- target to beacon at time $\hat{t}_1$

$\quad = \Delta R + R_1 - R_3$

$\bar{h}_T$ = Target altitude at time t_{3S}

$\dot{h}_T$ = Target altitude rate (provided by tracker)

(f) h_T = Target altitude at time $\hat{t}_i$

$\quad = \bar{h}_T + \dot{h}_T(\hat{t}_1 - t_{3S})$

$\Delta h = h_S - h_T$

Table A-3: Position Determination Procedure, DABS Environment (Option II)
(Continued)

d_1 = Ground range -- beacon to SS-CAS

$$= \left[R_1^2 - (h_S - h_B)^2 \right]^{\frac{1}{2}}$$

d_2 = Ground range -- beacon to target

$$= \left[R_2^2 - (h_S - h_B)^2 \right]^{\frac{1}{2}}$$

d_3 = Ground range -- SS-CAS to target

$$= \left[R_3^2 - \Delta h^2 \right]^{\frac{1}{2}}$$

$|\Delta \Psi|$ = Magnitude of differential azimuth at time $\hat{r}_1$

$$= \cos^{-1} \left(\frac{d_1^2 + d_2^2 - d_3^2}{2 d_1 d_2} \right)$$

S_Ψ = Algebraic sign of $\Delta \Psi$

$$= \text{sgn} \left(t_{SP2} - t_{TP2} \right)$$

$\Delta \Psi = S_\Psi |\Delta \Psi|$

Table A-3: Position Determination Procedure, DABS Environment (Option II) (Continued)

(h) ψ_T = Target azimuth at time $\hat{t}_1$

$= \psi_S + \Delta\psi$

N_S = North coordinate of SS-CAS relative to beacon

$= d_1 \cos \psi_S$

E_S = East coordinate of SS-CAS relative to beacon

$= d_1 \sin \psi_S$

N_T = North coordinate of target relative to beacon

$= d_2 \cos \psi_T$

E_T = East coordinate of target relative to beacon

$= d_2 \sin \psi_T$

A-16

Table A-3: Position Determination Procedure, DABS Environment (Option II)
(Continued)

$\sigma_N = \text{sgn} \ (N_T - N_S)$

$\sigma_E = \text{sgn} \ (E_T - N_S)$

(i) β = Target bearing relative to SS-CAS at time $\hat{t}_1$

$= \tan^{-1} \left[\dfrac{E_T - E_S}{N_T - N_S} \right]$: quadrant assigned according to

		σ_E	
		+	−
σ_N	+	I	II
	−	IV	III

A-17

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